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THE 1200-VOLT RAILROAD—A STUDY OF ITS VALUE FOR INTERURBAN RAILWAYS

BY CHARLES E. EVELETH

The various 1200-volt interurban railways have now been operating a sufficient length of time to prove that there are no material objections to the use of this voltage on passenger cars. The nature of such minor difficulties as have been experienced have been such that their correction has required only detail changes of design which have been readily made. The important items of reliability and low cost of upkeep have met all expectations.

A single statement regarding the motors may explain the reason for this successful performance. On the Pittsburg, Harmony, Butler & Newcastle line where the service is unusually severe on account of grades and curves, a considerable number of the brushes originally shipped in the motor brush holders are still in service, though many motors have now run over 150,000 car miles, and the wear on the commutators is hardly perceptible. It can be stated from the performance of the 1200-volt system that nothing is jeopardized by the adoption of this system, and such economies as are possible by its use can generally be obtained without offsetting disadvantages.

We may therefore assume that the 1200-volt system has "found itself" and a new system is thereby made available for consideration when studying the requirements of new railroads or extensions to existing systems. If desired, the cars may be run at equal efficiency and speed over tracks equipped for 600 volts.

This being the case, the question naturally arises, what gains may be expected from the use of this higher voltage?

The primary object of any railway is to pay dividends and these are limited by the amount of the receipts which must be expended for two items,—fixed charges, and operation. The most inflexible item is fixed charges. This works twenty-four hours a day whether business is good or bad and never gives up any ground once gained. Its only vulnerable point is the first cost of the railway. The 1200-volt system now offers a practical way of reducing the first cost of electrification through the material saving in substations and secondary distribution conductors. This gain becomes a permanent asset of the railroad, making a definite decrease in the fixed charges at a place which cannot be reached in any way except by raising the voltage.

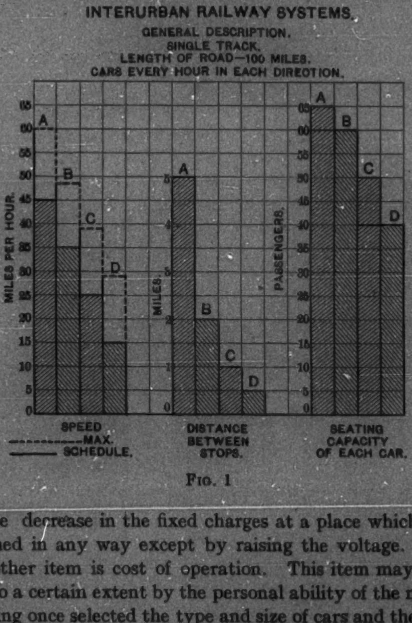

Fig. 1

The other item is cost of operation. This item may be controlled to a certain extent by the personal ability of the manager, but having once selected the type and size of cars and the voltage of the system it is practically impossible for him to materially change the cost of getting power to his cars, which depends upon the distribution efficiency of his system and the cost of substation operation. The 1200-volt system decreases the cost of getting power to the cars in two ways; first, reducing the number of substations, and second, increasing the substation efficiency by improving the load factor. This latter result may seem unreasonable at first thought until one considers upon what grounds substation units are selected. They are not selected on the basis of heating, for it is probable that there are few interurban stations in this country running with 50 per cent machine load factor, and the average is certainly below 30 per cent for ordinary interurban conditions. It is generally necessary for the station unit to commutate within its overload guarantees, the maximum starting current of at least two trains starting simultaneously. As the running current of a train is about one third of the starting current, and there are considerable periods during coasting and stops when the train is taking no current, and, furthermore, there are generally times when no trains are on the section fed by an individual substation, the low load factor can readily be accounted for. If then the units are selected for peak conditions the capacity of each station will remain constant independent of the number of stations. It is evident when decreasing the number of substations, that is, increasing the track mileage fed by each station, that the average load will be greater and the substation load factor and efficiency improved. The total substation cost and operation will be decreased practically in proportion to the reduction in the number of stations. These advantages are net advantages since they are, in the 1200-volt system, obtained without being offset by extraordinary car equipment maintenance.

Any railway is complex, but there are certain fundamental differences, namely track mileage, size of trains units, and schedule speeds, which have a definite influence on the cost of electrification. In order to obtain an idea of the advantages which may be expected with the use of 1200 volts as contrasted with 600 volts, let us consider some concrete applications to different classes of conditions from which we may be able to draw some general conclusions.

DESCRIPTION OF RAILROADS

	A.	B.	C.	D.
Length of road, miles, all single track	100	100	100	100
Time between trains each direction, minutes	60	60	60	60
Cars per train	3	1	1	1
Seating capacity per car	65	60	50	40
Distance between stops, miles	5	2	1	0.5
Schedule speed, miles per hour	45	35	25	15
Maximum speeds, miles per hour	60	48	38	28
Car-miles per day	9000	3000	3000	3000

In making these comparisons conservative values have been used, such as low substation costs, high cost of 1200-volt car maintenance, etc. so that the results will be conservative and the advantage rather less than might actually be achieved.

It will be seen that the roads vary greatly in conditions, from the heavy railroad conditions of *A*, through heavy interurban *B*, light interurban *C*, and very light traffic *D*. In fact, the cars of *D* will be no heavier than many city cars. See also Fig. 1.

Cars. Based upon the requirements, the following data may be considered reasonable for the cars.

CARS
GENERAL DATA

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Number	60	60	15	15	17	17	20	20
Cost each	$15,000	$13,000	$11,000	$10,000	$8,000	$7,000	$5,000	$4,500
Weight, tons	46.5	45	36	35	27	26	18	17
Amperes, starting	1200	2200	280	520	200	370	120	220
" running	300	574	94	174	66	124	40	74
Kw-hr. per train mile	11.16	10.8	2.88	2.80	1.89	1.82	1.08	1.02
Car-miles per day per car	150	150	200	200	176	176	150	150

It will be noticed that the power consumption which is "at the train" is slightly more for the 1200-volt cars on account of the greater weight of their equipments.

CARS
COST OF MAINTENANCE
Cents Per Car-Mile

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Mechanical	1.25	1.25	1.00	1.00	.90	.90	.75	.75
Electrical	.99	.90	.77	.70	.60	.55	.55	.50
Total	2.24	2.15	1.77	1.70	1.50	1.45	1.30	1.25
Yearly cost	$73,500	$70,500	$19,400	$18,600	$16,400	$17,000	$14,300	$13,700

In this estimate, 10 per cent greater maintenance is allowed for the up-keep of the 1200-volt electrical equipment. As a matter of fact up to the present time no noticeable increase has been observed.

Substations. In selecting the size of synchronous converter units for the stations they are in this case based on a maximum momentary demand of two cars starting simultaneously, except in the case of system *A* where the size is based on the demand of one train starting and one train running. In each case a reasonable margin is allowed for occasional additional service.

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Number of substations.....	6	14	4	9	3	6	3	5
Est. momenmentary demand, kw...	1,440	1,320	336	312	280	222	192	154
Number of units........	2	2	2	2	2	2	2	2
Size of each unit........	1,000	1,000	300	300	200	200	150	150
Cost of station, each...	$60,000	$56,000	$26,400	$24,000	$20,200	$18,400	$17,100	$15,600

The number of substations is dependent upon the maximum economical spacing, considered in conjunction with the cost of feeder copper and the allowable line drop with the assumed conditions of load. In each case it will be found that the addition of another substation to the number given in the data will not save its equivalent in cost of feeder copper. This brings up the question as to what may be considered equivalent feeder copper. The table below gives these equivalents.

EQUIVALANT FEEDER COPPER TO REPLACE ONE SUBSTATION

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Annual cost of labor and material........	$2,500	$2,500	$1,900	$1,900	$1,800	$1,800	$1,700	$1,700
Fixed charges........								
Interest........ 5%								
Depreciation.... 3%								
Taxes and insurance.......... 3%								
Total........11%	6,600	6,160	2,904	2.640	2,222	2,024	1,881	1,716
Total....	$9,100	8,760	4,804	4,540	4,022	3,824	3,581	3,416
For feeder copper the interest, etc., will be approx. 8½ per cent								
Investment in feeder copper equivalent to each substa. will be..	$110,000	106,000	$58,300	$55,000	$38,800	$46,400	$43,400	$41,400

The acutal amount should be somewhat greater than these values, for with the addition of a substation there is a reduction in load factor on each substation, lowering the distribution efficiency. A curve is given, Fig. 2, to show the change in substation efficiency with change in the load factor on individual synchronous converters. This curve is for a station having 150-kw. to 300-kw. units. For the larger machines the curve would be about two per cent higher.

It will be seen that the investment in feeder copper which must be saved to justify an additional substation will be approximately 2½ times the cost of the substation.

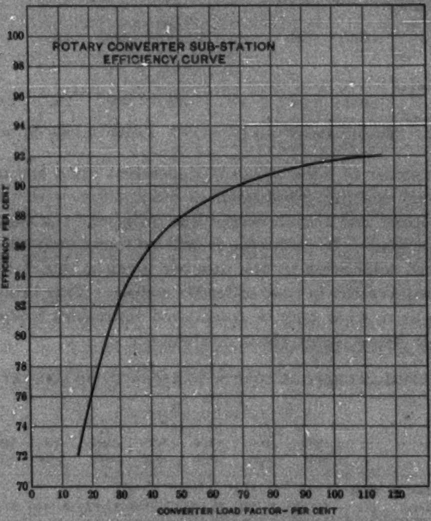

Fig. 2

An examination of the diagram, Fig. 3, showing the "location of substations" will give a fairly comprehensive view of the railroad lay out and the location of the cars at any hour.

Primary Distribution. This in each case will be the same for either system, except that the total length of the 600-volt transmission line will be slightly longer on account of the greater distance between the terminal stations. A flat price of $3,500 per mile of transmission line is taken for system *A*, and $1,000 per mile for system *B*, *C*, and *D*.

It will make practically no difference where the power is fed to the high tension system. For the sake of simplicity it is assumed that power is purchased and delivered to the power house step-up transformers at one cent per kw-hr.

Secondary Distribution. Track. For railroad *A*, 85-lb. rail is assumed. This has a resistance per mile, including bonding,

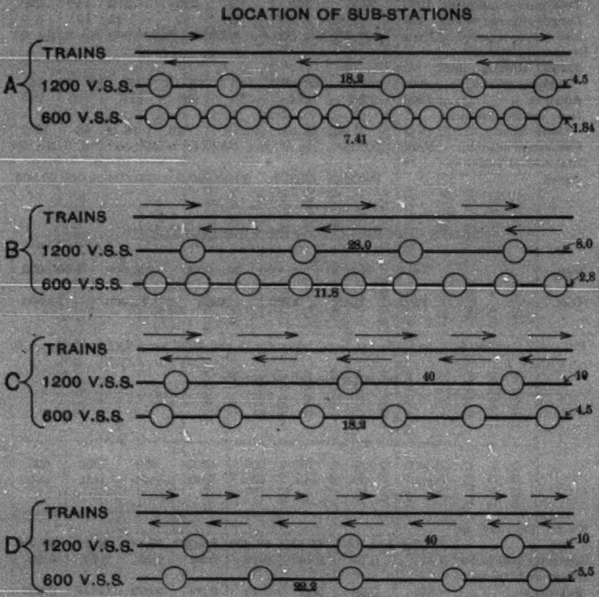
LOCATION OF SUB-STATIONS
A
TRAINS
1200 V.S.S.
18.2
4.5
600 V.S.S.
7.41
1.84
B
TRAINS
1200 V.S.S.
28.0
8.0
600 V.S.S.
11.8
2.8
C
TRAINS
1200 V.S.S.
40
10
600 V.S.S.
18.2
4.5
D
TRAINS
1200 V.S.S.
40
10
600 V.S.S.
22.2
5.5

Fig. 3

of approximately 0.033 ohm. The other roads use 70-lb. rail having a resistance per mile of 0.04 ohm. A third-rail equivalent to a 1,000,000-cir-mil. feeder is assumed for *A*, and No. 0000 trolley wire for the other roads. The values used in obtaining the feeder copper necessary are based on a maximum momentary drop of 250 volts for the 600-volt systems and 500 volts for the 1200-volt systems. This will give an average secondary distribution efficiency of approximately 90 per cent.

FEEDER COPPER REQUIREMENTS

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Stub End Calculations:								
Trains starting and running	1–S	1–S	1–S	1S	1S–1R	1–S	1–S	1–S
Total current, amperes	1200	2200	280	520	266	370	140	220
Length stub end miles,	4.5	1.85	8	28	10	45	10	5.5
Size copper required	None	1,000,000	No. 000	No. 0000	No. 00	300,000	No. 0	No. 00
Between Substations:								
Trains starting and running midway	1S	1S	1S–1R	1S	1S–1R	1S	1S–1R	1S
Amperes	1200	2200	374	520	266	370	160	220
Dist. between substations, miles	18.2	7.41	2.08	11.8	40	18.2	40	22.2
Size copper required	None	1,000,000	No. 0	No. 0000	No. 00	300,000	No. 0	No. 00
Total cost of feeder installed		290,000	53,200	80,000	60,000	100,000	50,000	60,000

FEEDER COPPER—COST PER MILE INSTALLED

Size	No. 0	No. 00	No. 000	No. 0000	300,000	1,000,000
Cost	$500	$600	$700	$800	$1,000	$2,900

For track bonding $450 per mile has been taken for *A* and $400 per mile for *B*, *C* and *D*.

POWER CONSUMPTION

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Kw-hr. per day at cars	$33,500	$32,400	$8,640	$8,400	$5,670	$5,470	$3,240	$3,060
Converter load factor	0.31	0.13	0.44	0.19	0.58	0.28	0.45	0.25
Efficiency (average)								
Substation	0.836	0.69	0.87	0.76	0.39	0.823	0.873	0.803
Secondary distribution	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Transmission	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Step-up transformers	0.98	0.98	0.97	0.97	0.97	0.97	0.97	0.97
Combined	0.722	0.595	0.745	0.632	0.761	0.705	0.748	0.688
Kw-hr. per day purchased)	46,500	54,500	11,600	13,300	7,450	7,750	4,330	4,440
Cost per year at one cent per kw-hr.	$169,000	$199,000	$42,400	$48,600	$27,200	$28,200	$15,800	$16,200

SUMMARY OF COSTS
ELECTRIFICATION MATERIAL

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Cars	$960,000	$840,000	$172,500	$150,000	$136,000	$119,000	$100,000	$90,000
Substations	360,000	784,000	106,000	216,000	61,000	110,000	51,000	78,000
Transmission	318,000	340,000	84,000	94,000	80,000	91,000	80,000	88,000
Trolley*	625,000	600,000	160,000	160,000	160,000	150,000	160,000	150,000
Feeder	None	300,000	53,000	80,000	60,000	100,000	50,000	60,000
Bonding	43,000	43,000	40,000	40,000	40,000	40,000	40,000	40,000
	2,308,000	2,909,000	615,500	730,000	537,000	610,000	481,000	506,000
Track, roadway, etc.	2,500,000	2,500,000	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
Total	$4,808,000	$5,409,000	$2,415,500	$2,530,000	$2,337,000	$2,410,000	$2,281,000	$2,506,000
Note:								
Substation buildings	45,000	105,000	20,000	45,000	14,000	29,000	14,000	23,000
Substation electric equipment	315,000	679,000	86,000	171,000	47,000	81,000	37,000	55,000
Cars and substations	1,320,000	1,624,000	278,500	386,000	197,000	229,000	151,000	69,000
Distribution materials	998,000	1,285,000	337,000	364,000	340,000	381,000	330,000	338,000

* Third rail used on *A*.

FIXED CHARGES
ELECTRIFICATION MATERIAL

	Life years	Annuity 5 per cent	A		B		C		D	
			1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Depreciation										
Cars	15	46.34	$44,500	$39,000	$8,000	$7,000	$6,300	$5,500	$4,600	$4,200
Substation buildings	30	15.05	700	1,600	300	700	200	400	200	300
Substation apparatus	20	30.24	9,500	20,500	2,600	5,200	1,400	2,400	1,100	1,700
Transmission	20	30.24	9,600	10,300	2,500	2,800	2,400	2,700	2,400	2,700
Trolley	12	*62.83	18,900	18,100	10,100	9,400	10,100	9,400	10,100	9,400
Feeders	20	30.24	—	9,100	1,600	2,400	1,800	3,000	1,500	1,800
Bonding	10	79.50	3,600	3,600	3,200	3,200	3,200	3,200	3,200	3,200
			86,800	102,200	28,300	30,700	25,400	26,600	23,100	23,300
Interest: 5 per cent on total cost of electrification material			116,000	145,000	31,000	36,000	27,000	30,000	24,000	2,500
Taxes: 1½ per cent of total cost of electrification material			36,400	43,700	9,200	11,000	8,000	9,100	7,200	7,600
Insurance: 1½ per cent of cost of rolling stock and substations			19,800	24,200	4,200	5,500	2,000	3,400	2,200	2,500
Total fixed charges			259,000	315,100	72,700	83,200	62,400	69,100	56,500	58,400

* Third-rail depreciation based on 20 years life.

COST OF OPERATION AND MAINTENANCE

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
Transmission	$9,000	$9,500	$3,000	$3,300	$2,800	$3,200	$2,800	$3,100
Trolley and feeders	15,000	15,000	9,000	9,000	9,000	9,000	9,000	9,000
Rolling stock	73,500	70,500	19,500	18,500	16,500	17,000	14,500	15,000
Substations	15,000	35,000	7,600	17,000	5,500	11,000	5,000	8,500
Cost of power	169,000	199,000	42,400	48,600	27,200	28,200	15,800	16,200
	281,500	329,000	81,500	97,100	61,000	68,400	47,100	50,800
Total operation and maintenance of items listed	282,000	329,000	82,000	97,000	61,000	68,000	47,000	51,000
Statistics indicate that the items listed on 600-volt roads constitute approximately 44 per cent of the total operating cost. Based upon this there should be added to each of the above	421,000	421,000	123,000	123,000	87,000	87,000	65,000	65,000
Total yearly cost of operation and maintenance of 3,285,000 car-miles per year for *A* and 1,095,000 car-miles per year for *B*, *C* and *D*	703,000	750,000	205,000	220,000	148,000	155,000	112,000	116,000

COMPARISON OF SYSTEMS

	A		B		C		D	
	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt	1200 volt	600 volt
I.—First Cost:								
Track, roadway, etc.	$2,500,000	$2,500,000	$1,800,000	$1,800,000	$1,800,000	$1,800,000	$1,800,000	$1,800,000
Electrification material								
Car equipments	960,000	840,000	172,500	150,000	136,000	119,000	100,000	90,000
Substations	360,000	784,000	106,000	216,000	61,000	110,000	51,000	78,000
Distribution	988,000	1,285,000	337,000	364,000	340,000	381,000	330,000	338,000
Total	$4,808,000	$5,409,000	$2,415,500	$2,530,000	$2,337,000	$2,410,000	$2,281,000	$2,303,000
In favor of 1200 volts	—	601,000	—	114,500	—	73,000	—	26,000
II.—Fixed Charges:								
Track, roadway, etc., 7 per cent	175,000	175,000	126,000	126,000	126,000	126,000	126,000	126,000
Electrification material	259,000	315,000	73,000	83,000	62,000	69,000	56,500	58,500
Total	434,000	490,000	209,000	209,000	188,000	195,000	182,500	184,500
In favor of 1200 volts	—	56,000	—	10,000	—	7,000	—	2,000
III.—Operation and Maintenance:								
Miscellaneous	421,000	421,000	123,000	123,000	87,000	87,000	65,000	65,000
Electrical	282,000	329,000	83,000	97,000	61,000	68,000	47,000	31,000
Total	703,000	750,000	205,000	220,000	148,000	155,000	112,000	116,000
In favor of 1200 volts	—	47,000	—	15,000	—	7,000	—	4,000
IV.—Annual Cost II+III	$1,137,000	1,240,000	414,000	429,000	336,000	350,000	294,500	300,500
In favor of 1200 volts	—	103,000	—	2,500	—	14,000	—	6,000
V.—Revenue:								
Additional receipts per car-mile necessary to pay additional cost of operation, etc., for 600 volts	—	3.1c.	—	2.28c.	—	1.28c.	—	0.55c.

NOTE.—3,285,000 car-miles per year for *A*.
1,095,000 car-miles per year for *B*, *C*, and *D*.

COMPARISON OF SYSTEMS

	600 volt per cent	A 1200 volt per cent	B 1200 volt per cent	C 1200 volt per cent	D 1200 volt per cent
I.—First Cost:					
All electrification material..........	100	79.4	85.5	88.0	95.0
II.—Fixed Charges:					
All electrification material..........	100	82.3	87.3	90.0	96.5
III.—Operation and Maintenance:					
All electrification material..........	100	85.8	84.5	89.9	92.0
IV.—Annual Cost II+ III:					
All electrification material..........	100	84.0	86.0	90.0	94.0

COMPARISON OF 600 V. & 1200 V.
RAILWAY SYSTEMS.

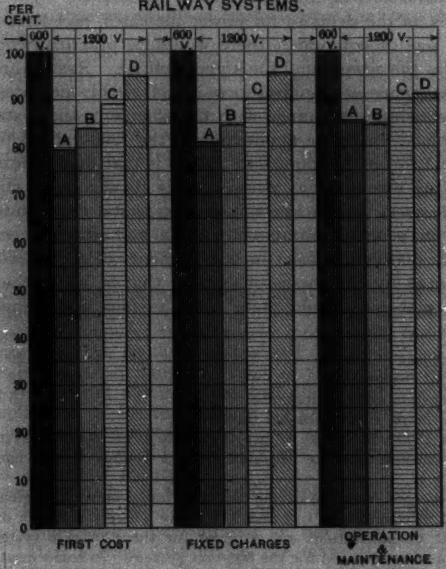

FIG. 4

In electrification material there is included under "first cost" and "fixed charges," (I and II) cars and car equipments, substations complete, transmission line, trolley or third rail, low tension feeders and track bonding.

Under "operation and maintenance" (III) of electrification material there is included rolling stock, substations, trolley, feeders and track bonding, and cost of power, *i. e.* all items which are affected by choice of system. Platform charges, general expenses, etc, common to both systems are not included.

On examination of these results, which are based on conservative figures on account of the relative newness of the 1200-volt system, it is apparent that the higher voltage effects economies at points that can only be reached by a change more fundamental than is possible with the lower voltage.

The saving of 1½ to 2 cents per car mile will permit a very material increase in dividends.

It is further clear that the relative value of the higher voltage increases as the demand for power increases, and that below a certain size of equipment there would be practically no justification for the adoption of the higher voltage. Results are shown for convenience in graphical form Fig. 4, as this indicates clearly how the economies change with the change in the system.

The place where the application of the 1200-volt system may be looked for in the immediate future is that field of interurban railroading where it has already made its successful start.

Conclusion. In conclusion it appears that a conservative estimate of the economy obtained by a 1200-volt system as compared with the 600-volt system in the elements of a railroad which are effected by the choice of system, that is, all of the electrification material, would place these savings approximately as follows:

1. First cost..10 to 20 per cent
2. Fixed charges...................................10 to 18 per cent
3. Operation and maintenance.....................10 to 15 per cent

Furthermore, experience has shown that

4. The 1200-volt system is just as reliable as the 600-volt system.
5. Substations may be operated from a system of any commercial frequency.
6. In specific cases the saving has been found materially greater than indicated in conclusions 1, 2 and 3, notably where the length of road is such that no substations are required for the 1200-volt system while substations are required for the 600-volt system. In some insatnces the savings have been as great as 25 or 30 per cent in the electrification material.

DISCUSSION ON "THE TWELVE HUNDRED-VOLT DIRECT-CURRENT RAILWAY SYSTEM." PHILADELPHIA, JANUARY 10, 1910

W. S. Murray: I want to speak of the New York New Haven and Hartford system, because in reviewing the paper tonight, I find that Mr. Eveleth has not mentioned, throughout all of his interesting lines, the single-phase system.

It is to be noted that the discussion is strictly direct current vs. direct current, and not direct current vs. alternating current. I believe there is a zone which is a function of traffic or distance, not the combination of both, but the one or the other, which requires the use of a system as brought out in Mr. Eveleth's paper.

I should have been very much interested, if, in the classification that Mr. Eveleth has used (*A*, *B*, *C*, and *D*), a third system, the single-phase, had been introduced for comparison.

I want to try to acquaint you with the conditions that exist on the New Haven road in comparison with the conditions cited. For example in *A* the heaviest conditions are used. Let us assume the cars weigh 60 tons apiece, or say 80 tons. Three of them will total between 180 and 240 tons for the train. Now with the New Haven, our trains run up to a maximum of 800 tons. Our minimum weight of trains is over the maximum *A* conditions.

I cannot pay too high a compliment to Mr. Eveleth for the earnest effort his paper indicates. I would like to say this, however, that I think it is slightly more academic than would be the case if he had actual field data from which to make the compilations. The 1200-volt system, of course, has not been sufficiently long in operation to afford comparison, but the framework and the synopsis of the whole scheme is so well arranged that the highest tribute is due Mr. Eveleth for the manner in which he has put it together; and in the future, when electrical engineers are collecting such data, I can think of no better arrangement than the one which Mr. Eveleth has laid before us.

One thing that struck me as important is the question of motor slip on the 1200-volt system. It is quite evident that eventually this system will include the 1200-volt motor itself, but it is the combination of the 600-volt motor and 1200-volt line that is included in the paper tonight. Thus, in the event of the motor slipping it does not eliminate the bad effect that would result in the collection of the full voltage across the terminals of the motor, and while low motor speed would take care of mechanical difficulties, the slip would inevitably lead to commutator flashovers of a serious nature.

Reference is made to the conditions of a 250-volt drop in a 500-volt line, or a 500-volt drop in a 1200-volt line. Some electrical engineer has paraphrased an old saying, which now reads: "It is voltage that makes the mare go." In order to find out the drop in the New Haven system during the rush hours of the morning and afternoon, voltmeter readings were taken at Woodlawn, 18 miles from the power station. The voltage never fell below 9,800.

Another point in this paper is that the calculations are based on theoretical assumptions of trains taking current in the vicinity of substations. Upon the basis of this assumption many of the financial considerations of the paper are involved, and one can see in an instant that this is the crux of the whole situation. If I had attempted to write the paper, I should have made the same assumption. While it seems perfectly reasonable to make these assumptions, at the same time this brings out the academic feature to which I have referred, and emphasizes the fact that we lack the data of actual 1200-volt practice.

One point I want to make tonight, more than anything else, is that electricity can certainly wear a great many different suits of clothes. I think the 1200-volt system has come to stay, and that it is applicable to certain classes of interurban service. The first reason, to me, for its adaptability to these conditions is, that it does away with something that has been a nightmare to us, particularly on the New Haven road. In nearly every city there is and will be direct current. One of the earliest mistakes made with the single-phase was the attempt to combine it with direct current. I would like nothing more than to be able to eliminate direct current from our system. I think the best reasons for the existence of the 1200-volt system are the excellent opportunity it affords for the reduction or elimination of substations in rural territory, and the facility with which motors operating on lines of this voltage can be made to accommodate themselves to equally efficient operation on 600-volt city lines, bringing into sharp contrast the obnoxious arrangement of the combined alternating and direct current equipment.

Dr. Hutchinson has recently given us an interesting paper in which he has cited the true conditions for the application of a three-phase system. Just as the 1200-volt system will be applicable to interurban roads, conditions will likewise be met in another case, where the three-phase must step in as the preferred system. That system which figures the least first cost and operating expense must rule. That is one thing I think we ought to realize, namely, that, if we make a success of something, it does not necessarily follow that it applies to everything else.

Now I want to acquaint you a little more thoroughly with the New York, New Haven & Hartford conditions. First, it is a trunk line proposition; 60 miles of four-track road. This mileage covered the primary consideration, with its possible extension to Boston, the total distance of which would then be 220 miles. As I have stated before, our passenger train weights reach a maximum of 800 tons, and the service between New Haven and New York would require as many as 175 trains daily. On the freight side of the schedule, trains of 1500 tons are common;

the average being in the neighborhood of 1200 tons, and as many as 80 of these trains are in daily operation between New Haven and New York. In reviewing these conditions it is clear that nothing under the classification of *A*, *B*, *C* and *D* even approximates them.

The history of alternating current shows that it has steadily replaced direct current wherever power and distance are involved. What greater field for the application of this agency exists, than an 800-ton Pullman train which may be seen standing in the Grand Central station, with sign boards marked "Boston." As an electrical engineer, is not your first mental conception of this train associated with power and distance?

One of the points in Mr. Eveleth's paper that has particularly interested me, is the gradual betterment in first cost and operating expenses by the use of a 1200-volt system in preference to the 600-volt, as it passes from the conditions imposed by city requirements to light interurban traffic, and finally to those conditions required in heavy interurban traffic. This suggests to me the system that comes into play after the 1200-volt system has done its best. It is fair to assume that 1200 volts on the direct-current motor will not be exceeded. Thus, with the motors in series it is possible to establish a 2400-volt line. This may widen the field of application of the 1200-volt system for interurban work, but its competition under trunk line conditions, such as obtain on the New Haven road, disappears when compared with single-phase current with 11,000 volts overhead. There is nothing to prevent a higher voltage than 11,000. It is not impossible to conceive of 22,000-volt transcontinental lines for the future. The increase of voltage by direct-current system is limited on account of the impossible condition imposed of increasing the voltage of the motor to an impracticable point, while in the case of the single-phase system the very antithesis of this condition holds, in that it is perfectly possible to raise the line voltage and reduce the motor voltage even lower than that at present used.

In connection with a single-phase system, I wish to say that I thoroughly believe its principal application is relegated to just one thing, trunk line traffic. I do not think, except for isolated branch or interurban lines that come within the zone of power supply from a trunk line system, that it is applicable to interurban or city lines, but I believe it is the only system today which can produce the economies that a railroad president and his board of directors would listen to, in the matter of steam road electrification.

Now a word as to why I believe this. One of the greatest and most unproductive mileages of steam lines in the eastern territory consists of yards, sidings and branch lines. In such territory as is involved by our Atlantic coast lines, let us say between Boston, and, for the present, Washington, think of the innumerable yards that must be electrified in order to handle freight by electricity. The greatest economy can only be obtained by using high voltage power. Mr. Stillwell compiled some very interesting figures in regard to the efficiency of electricity for steam railroad traction. Using some twenty steam locomotives over a long period of test we have been able to corroborate these figures, and establish the ratio of 1 to 2, for coal burned in electric vs. steam traction, with the density of traffic, for instance, such as exists on the New Haven road. It is unquestionably true that if these large areas are to be electrified it will be impossible on a direct-current basis to put up a sufficient amount of copper to handle with proper economy the requirements in the yards for switch and road engine work. We must go to the high-voltage low-priced conductor. The use of the third-rail is prohibitive, for two reasons; first, it is dangerous; and second, the costs involved are on a lineal basis; that is to say, it may be feasible to lay down a main line third rail, but in the case of yards it fails in comparison with the economies that can be effected by the overhead conductor. The cost of the overhead system in yards has been reduced to about one half, or perhaps 35 per cent, of the cost of main line electrification, and in this way these large unproductive areas may be taken care of.

L. B. Stillwell: I should like to point out briefly certain general considerations which engineers should keep in mind when they have occasion to deal with this problem of selecting a system for the electrical equipment of interurban or other railway lines.

While the problem presents itself in each instance as a question of selection of a system to meet certain definite requirements, a correct solution must take into account certain general considerations which at first sight are not obviously included in the local problem.

We have in the United States something like 220,000 miles of railway lines operated by steam. We have in our cities and towns many thousands of miles of track used by electrically-driven equipment and practically all of this equipment is operated by direct current at a potential of from 500 to 600 volts.

Outside our cities, great progress has been made in supplementing transportation facilities by what are generally called interurban railways. In Illinois, Indiana and Ohio, approximately 25 per cent of the aggregate steam railroad mileage is today paralleled by these interurban electric lines. These for the most part are operated by the direct-current system at 600 volts, but a few are using the single-phase alternating-current system and a few others recently have been equipped with 1200-volt direct-current apparatus.

Several of the great steam railroad companies recently have expended large sums of money in equipping certain of their terminals in large cities with electric power and at least one (the Great Northern Railroad) is using electricity to operate its trains on a short section of a mountain division where special difficulties imposed by tunnel and grade had to be met.

It requires no argument to prove that the time has arrived in the application of electric motive power to transportation when special solutions adapted to specific local problems should be avoided unless they are in line with general tendencies; in other words, engineers investing millions of other peoples' money are bound to direct these expenditures, so far as practicable, along lines which recognize the natural and inevitable tendency in railroad work to standardize everything essential to interchange of traffic.

Mr. Eveleth's paper admirably compares the 1200-volt and the 600-volt direct-current systems in the field of interurban transportation and, within the limits of the problem which he considers, the advantages of the 1200-volt system are manifest. Broadly speaking, his paper presents figures which show that the higher voltage possesses advantages which in certain kinds of service are more than an offset to its disadvantages.

It is an obvious and fair deduction that the possibilities and limitations of voltages still higher must be carefully considered. A comparison of the 1200-volt direct-current system with a 10,000-volt single-phase or three-phase alternating-current system, as applied to the operation of heavy passenger and freight trains such as are operated by the steam railroads of the country, would show advantages for the latter analagous to those which the 1200-volt system possesses when compared with the 600-volt system in the class of service which Mr. Eveleth considers.

There are two methods by which electric railway service outside the zone of natural application of the 600-volt system can be standardized with respect to those things which are essential to interchange of rolling stock. One is the method which Germany has adopted. Essentially it consists in (1) careful study by a competent commission of the broad problem of railway electrification; (2) selection of that system which present knowledge points to as best adapted to a general solution; and (3) concentration of effort in perfecting the details of a system selected.

The other is the method which thus far we are trusting to in America. This method assumes that each specific problem of electrification is to be considered independently of present or future relations. It ignores the obvious fact that the horizon of present "zones of electrification" is sure to expand in the near future and that these horizons in many instances are certain to overlap before the expiration of a proper period of amortization of the capital invested in the apparatus selected. It trusts to the future to find a method of writing off whatever capital may be wasted by reason of short-sighted special solutions, secure apparently in the conviction that the owners of the property will find a method, and also equally secure in the belief that the premature scrap heap is not a source of loss to the manufacturer of electrical apparatus whatever it may represent to the purchaser.

One question which engineers should keep carefully in mind is this: What part is the 1200-volt system destined to play in the future extension of the application of electric motive power to transportation.

Germany has adopted the single-phase system at 15 cycles and 10,000 volts.

In America, opinion is divided. We are using as substitutes for steam locomotives the single-phase alternating-current system at 25 cycles and 11,000 volts, the three-phase alternating-current system at 25 cycles and 6600 volts, the direct-current system at 600 volts; and in each case electric locomotives more powerful than the heavy steam locomotives which they displaced are in effective and satisfactory service. The consensus of opinion now is in favor of 15 cycles rather than 25 cycles for single-phase working and, as Mr. Eveleth has shown, the 1200-volt direct-current system possesses substantial advantages as compared with the 600 volt direct-current system for work outside city boundaries. The difficulty which electricity faces, therefore, in challenging the superiority of steam in the field of transportation is not poverty of resources but embarrassment of riches.

Two years ago, Mr. H. St. Clair Putnam and the speaker presented a paper before the Institute in which we advocated the early standardization of those things essential to interchange of traffic, *e. g.*, the location of third rail, the frequency used in alternating-current systems, and the height of the overhead trolley. The cross fire under which we found ourselves was unusually animated and vigorous. Since that time, however, some progress has been made. The engineers of both the leading American companies manufacturing electrical apparatus for traction purposes agree that where single-phase apparatus is used the frequency should be 15 cycles per second. Probably it is safe to assume also that the height of the trolley wire above track in the case of single-phase equipment has been practically agreed upon; at any rate, the New Haven engineers have selected a height which appears to meet all requirements and any engineer who may adopt in future a different location will find it necessary to justify his choice by very strong reasons.

In the cities we have the 600-volt direct-current system. Few will dispute that if we were today called upon to electrify any very large proportion of the existing steam railroads of the United States the 15-cycle single-phase alternating-current system would be chosen. Undoubtedly the use of other systems, such as the 1200-volt direct-current system, under conditions and for certain kinds of service intermediate between the trolley service of the city and trunk line service on our great railways, is justified in certain cases, but the engineer who recognizes tendencies and recalls the rapidity with which the use of electricity has expanded hitherto in the fields which it has entered, will be reluctant to adopt an intermediate system except in cases where his decision rests upon reasons unquestionably controlling.

C .E. Eveleth: You may expect to hear me express an opinion as to whether or not the 1200-volt system would be adequate for the New Haven situation. I do not consider myself in a position to express an opinion at this time. I am not sufficiently familiar with the conditions and have not studied the problem in detail to analyze the various requirements. Without a thorough study of the situation, a guess as to whether 1200-volts would or would not be applicable would be meaningless.

I agree with Mr. Murray's objections to the complications of the combined single-phase and direct-current systems. I heartily agree with Mr. Stillwell in his expression of opinion that we should go slowly about adopting any system that will add complication to a situation already very complicated. Both of these conditions were borne in mind and it was to meet both of these broad and very important considerations that the particular potential of 1200-volts has been selected instead of 1500, 1800 and 2000, any of which would have been applicable for interurban practice. By the use of 1200 volts direct current on the trolley, and motors wound for 600 volts, the car may be operated at the same speed on either 600- or 1200-volt trolleys by connecting the motors all in parallel for 600-volt operation and two in series and two groups in parallel on a 1200-volt section. By exactly doubling the voltage we thus take advantage of the economy of higher voltage with minimum complication of equipment.

One road is now successfully running with motors wound directly for 1200 volts on each commutator. The choice of individual motor voltage is one of the questions which must be considered in any particular case, as they may be wound for either 600 or 1200 volts.

The reason I have gone no further in the comparisons than conditions assumed under *A* is merely that the 1200-volt system is a new arrival and I do not know into what field it may extend. In this connection I am reminded of the answer that Benjamin Franklin gave to some inquirer who had seen the first baloon ascension. The man asked what good it was and Franklin said: "What good is a new born baby?" We cannot tell and we do not know where these things are going to end.

The trend of the future will depend on the operation of what we have, to a very large extent. What has been done in electrification of steam roads is comparatively small. Even in the case of the N. Y. N. H. & H. R. R. it is my understanding that the total cost of electrification is only about 3 per cent of the investment which the New Haven road has made for improvements in its system in the last seven years. Looking at the matter broadly, for the sake of unification we could afford to discard the millions of the present investments in steam road electrification if a commission along the lines that Mr. Stillwell mentioned were sufficiently competent and foresighted to decide on exactly the right system for future development.

Conditions in this country are vastly different from the conditions abroad. The Government here has practically no control over the equipment of railroads. The principal influence there, which is unknown to us, is the question of military transportation which, for flexibility, necessitates a uniform equipment for an entire country.

The choice of a system for heavy traction is quite a different problem from the choice for interurban service. Just as one tool fits one class of work, and another tool fits another class of work so there seems to be at the present time no one system best for all classes of service. I would regret very much to be considered an advocate of any one system. I hope to see the single-phase system ultimately make good because it has been the most promising from its inception on account of the apparent advantages in distribution, simplicity and cost.

A paper presented at the 242d meeting of the American Institute of Electrical Engineers, New York, January 14, 1910.

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ON THE SPACE ECONOMY OF THE SINGLE-PHASE SERIES MOTOR

BY WM. S. FRANKLIN AND STANLEY S. SEYFERT

It is not the object of this paper to argue for single-phase alternating-current electrification versus direct-current electrification, nor to argue for the locomotive versus the multiple-unit system of electric propulsion, nor to argue in favor of the axle motor as against the detached motor with side-bar or gear connections. The sole object of the paper is to discuss the question as to the maximum single-phase series motor rating that can be placed within a given space, and indeed the authors approach this question, not on an absolute basis, but on a basis of comparison. Given a well-designed single-phase alternating-current series motor of the usual construction, as represented, for example, by the motors of the present locomotives of the New York, New Haven & Hartford Railroad (and every one who has seen these motors in operation must admit that they represent a splendid achievement on the part of their designer) the question is how great an increase of rating can be realized by certain alterations in the design and by the use of certain new auxiliary devices. As will appear in the sequel, this question admits of a qualitative answer in every particular and of a quantitative answer in several important particulars.

A single-phase series motor differs from a direct-current motor:

1. Because its power-factor is less than unity.

2. Because of greater core losses and because of power loss due to short-circuit currents.

3. Because of a great tendency to spark at the commutator.

From the view-point of the operating engineer, however, these differences may present themselves as a single difference as follows:

(*a*) For a given frequency and rating, satisfactory operation may necessitate a very bulky and expensive motor; or

(*b*) For a given size and rating, satisfactory operation may require the use of a very low frequency; or

(*c*) For a given size, given frequency, and given rating, it may be impossible to realize satisfactory commutation.

Thus it may be said that the disadvantage of the single-phase series motor lies either in its excessive size, or in the necessity of using extremely low frequency, or in the unsatisfactory character of commutation. If, however, we choose a frequency of 25 cycles and set ourselves to meet the condition of satisfactory commutation—and we must meet this condition in any case—then the disadvantages of the single-phase motor reduce themselves solely to the question of size and weight. It is from this point of view that the authors approach the discussion of the single-phase series motor in this paper.

In a recent paper by Messrs. L. B. Stillwell and H. St. Clair Putnam,* the single-phase series motor problem was reduced to a question of frequency, and from this point of view they reached the following conclusions:

> * * * * * consideration of the facts now available lead us to conclude that notwithstanding the number and force of the arguments in favor of 25 cycles, a frequency of 15 cycles is preferable and should be adopted for heavy electric traction. The fundamental and, as it would appear, controlling reason which leads to this conclusion is the fact that within given dimensions a materially more powerful, efficient, and generally effective single-phase motor can be constructed for 15-cycle operation than is possible if 25 cycles be selected.
>
> * * * * *
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> In the case of multiple-unit equipment of passenger cars where locomotives are dispensed with and motors carried upon the car trucks, it is very important that the dimensions of motors be reduced to a minimum.
>
> * * * * *
>
> In the application of single-phase commutating motors to locomotives in general railway service, the minimizing of motor dimensions is perhaps still more important, although in this instance the limitations imposed by the space available are less obvious.

In the following discussion of the possibilities of space economy of the single-phase series motor, frequent reference will be made to the present electrical equipment of the New York, New Haven and Hartford Railroad, and the authors take occasion at this point to express their conviction that the equipment as it stands meets all of the conditions originally specified by the railroad company. This conviction is based in part upon a somewhat intimate personal association of the authors with the engineers of the New York, New Haven and Hartford Railroad, and in part upon the published records of the construction and operation of the equipment. No one claims, however, that the New Haven electrification represents a complete and satisfactory solution of the problem of heavy trunk-line electric traction. Indeed the authors have been assured by the New Haven engineers that the present equipment leaves much to be desired in the way of increase of motor-rating for a given weight of locomotive, especially an increase of tractive effort at starting. Mr. E. H. McHenry, for example, has not hesitated to state his opinion that greater and longer continued tractive effort, especially at starting, must be made possible without increase of weight.

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* *Transactions of American Institute of Electrical Engineers*, 1907, Vol. XXVI, Part I, pages 31–101.

Inasmuch as this paper refers almost wholly to matters of design, it is desirable to give a statement of the conditions which determine the design of a single-phase series motor.

(*a*) To produce a moderately large power-factor, and

(*b*) To reduce the tendency to spark at the brushes.

CONSIDERATION OF POWER-FACTOR

Fig. 1 is the well-known clock diagram in which I represents the current flowing through the motor, E the voltage acting across the motor terminals, $X_f I$ and $R_f I$ the reactance and resistance drops respectively in the field winding, $X_a I$ and $R_a I$ the reactance and resistance drops respectively in the armature and neutralizing windings combined, and E_c the induced counter electromotive force in the armature due to rotation. It is evident from this Fig. that a large power-factor (small value of the angle θ) depends upon a large value of E_c in comparison with $X_f I$ and $X_a I$. Of course $R_f I$ and $R_a I$ should both be as small as possible because they represent energy losses in the windings.

(*a*) In the first place the reactance $X_a I$ of the armature winding may be reduced nearly to zero by the use of the neutralizing winding.

(*b*) In the second place, consider the reactance drop $X_f I$ in the field winding. For a given frequency this is proportional to the product of the number of field turns and the maximum value of the alternating field-flux, exactly as in the case of the primary coil of a transformer. Assuming that we have a motor in which a specified maximum flux is to be produced, then to make the reactance voltage $X_f I$ a minimum, the machine must be designed so that the desired field flux may be produced by the least possible number of field turns. That is to say, the reluctance of the magnetic circuit must be small; or, in other words, the gap-space between the pole faces and the armature core must be short, and the iron of the field magnet and armature core must be operated at a low degree of magnetic saturation.

In the third place, the value of E_c may be increased for a given value of speed and given value of field flux by increasing the number of armature conductors. Therefore the use of a large amount of armature copper is an important feature of the single-phase series motor.

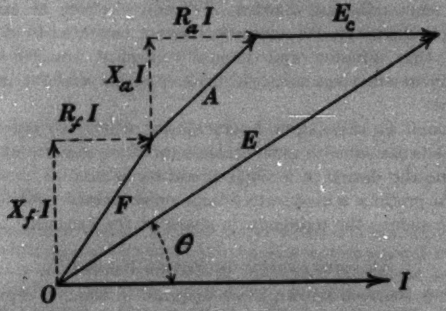

Fig. 1

In the fourth place, suppose we have a single-phase series motor running at given speed with given value (effective) of current and given value (effective or maximum) of field flux. Under these conditions E_c is definite in value (effective), the mechanical power $E_c I$ is definite, and a reduction of the frequency produces a proportional reduction of the reactance voltages $X_f I$ and $X_a I$ without affecting the value of E_c; that is, a reduction of frequency increases the power-factor of the motor. Therefore it is important to use low-frequency alternating current for a single-phase series motor.

CONSIDERATION OF SPARKING

A number of undesirable effects are included in the general term of sparking, as follows:

(*a*) The effects that are present in a direct-current machine and which are due to the necessity of a quick reversal of the current in a given armature section as the terminal bars (commutator bars) of the section pass under a brush; and

(*b*) The effects that are present in the alternating-current machine due to the excessive current which is produced in each short-circuited armature section by the pulsations of the field flux.

The first effect is quite familiar to designing engineers and need not be discussed here.*

The effects of excessive short-circuit currents due to pulsations of field flux are: to heat the armature winding; to heat the commutator; to heat the brushes; and to roughen the commutator by sparking. The remedy for these undesirable effects is of course to prevent excessive short-circuit currents and to shorten their duration as much as possible.

The electromotive force induced in a short-circuited armature section by the pulsating field flux is proportional to the number of turns of wire in the section, proportional to the maximum value reached by the pulsating field flux, and proportional to the frequency. Therefore the short-circuit current may be reduced by reducing the number of turns of wire per armature section—the resistance of the short-circuit not being reduced in proportion to the turns because of the relatively large resistance at the brush contacts—by reducing the maximum value of the pulsating field flux, and by reducing the frequency. It is essential, therefore, in the design of the single-phase series motor to provide for few turns of wire per armature section (many commutator bars); to provide for small field flux per pole (many field poles); and to use alternating current of low frequency.

The duration of short-circuit of an armature section by a brush is proportional to the thickness of the brush, and therefore it is desirable to use thin brushes. If the armature winding is of the simplex type, the necessary thickness of the brushes is determined solely by the necessary area of brush-contact to collect the given current. If the winding is of the multiplex type, a brush must never touch fewer than n commutator bars, where n is the number of constituent windings in the multiplex winding. In the multiplex winding, however, adjacent commutator bars do not form terminals of an armature section, and therefore the mere touching of two bars by a brush does not short circuit an armature section of a multiplex winding.*

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* A good discussion of this subject is given in a paper by W. L. Waters, *Transactions American Institute of Electrical Engineers*, 1904, Vol. XXIII, pages 365-378.

Special Devices for the Prevention of Sparking

The foregoing discussion refers to those general features of design which tend to reduce short-circuit currents in the armature sections of a single-phase series motor. It does not seem to be possible, however, to produce a single-phase series motor that will operate satisfactorily, without the use of special devices for the prevention of excessive short-circuit currents. The simplest device for this purpose is the insertion of a moderate amount of resistance in each commutator lead. This device is well known and need not be further discussed. A number of special inductive devices have also been proposed, and perhaps

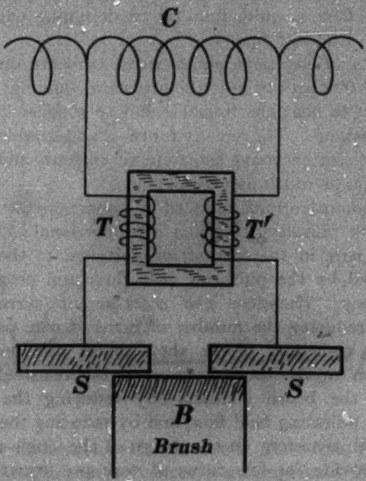

Fig. 2

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* It would be out of place here to discuss in detail the short-circuits which occur in a multiplex winding.

the best of these is the balanced choke-coil arrangement of S. S. Seyfert.

The essential features of the Seyfert arrangement may be seen in Fig. 2 in which C is a section of the armature winding, $S\ S$ are two commutator bars and T and T' are two coils on a small iron core. The two coils T and T' are so connected that their magnetizing actions on the iron core are equal and opposite when equal currents flow into (or out of) the armature winding through both coils; whereas their magnetizing actions work together when current tends to flow out of the armature winding through one coil and into the armature winding through the other coil. The resultant effect is that current can flow into or out of the armature through both coils T and T' without being choked, whereas opposite currents in the coils T and T' (due to the short-circuit current in the section) are greatly choked.

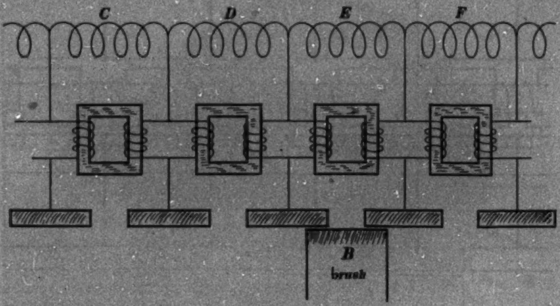

FIG. 3

Complete arrangement of the balanced choke-coils for a simplex armature winding are shown in Figs. 3 and 4. Fig.3 shows what the authors call the single-span connection which requires the use of narrow brushes, and Fig. 4 shows the double-span connection,* which permits of the use of a broad brush.

In order to test the efficacy of the balanced choke-coil arrangement, it was applied to a single-phase series motor which

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* Several distinct arrangements of the double-span connection are possible with a simplex winding, and a greater number of arrangements are possible with a multiplex winding. Ssome of these arrangements are much better than others.

was constructed and tested by Messrs. J. H. Wily and Geo. S. Mervine in 1905.† For the armature of this motor an old 25-h.p., 500-volt, Walker, direct-current, railway motor armature was used without any alterations except the addition of the system of choke-coils. The armature winding was a four-pole simplex wave, and it had three turns per armature section; that is, six turns between adjacent commutator bars. The commutator contained 97 segments. The armature core was 12.5 in. in diameter and 8.5 in. long. Two identical armatures were purchased, one to be used with and the other without balanced choke-coils. Fig. 5 shows the rosette of choke-coils nearly completed, and Fig. 6 exhibits the dimensions of the iron core

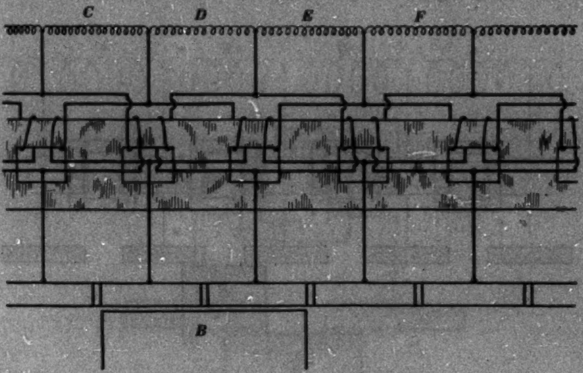

FIG. 4

structure. Each coil contained eight turns of No. 18 B. & S. copper wire. A general view of the completed armature is shown in Fig. 7. The field structure of this experimental motor was made* in the approved form with compensating windings placed in slots in the pole faces.

The ordinary speed, torque, and power-factor curves were determined for this motor as shown in Fig. 8. These tests were made with 30-cycle current from an old style high-frequency alternator driven at about one-quarter speed. It was found impossible to maintain full voltage throughout the test; in fact the pressure ranged from 275 volts when the current input was 23.2 amperes to 260 volts when the current input was 35.2 amperes.

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† See graduating thesis in Department of Electrical Engineering of Lehigh University.

* All of the sheet-iron stampings were made by Messrs. Wily and Mervine, dies being especially constructed for the purpose.

The pressure between adjacent commutator bars near the brushes was 19 volts effective when the motor current was 31.8 amperes, and yet the commutation was entirely satisfactory; even with a motor current of 35.2 amperes no more sparking was in evidence than is usual on a direct-current motor of the same size. Indeed the commutator was in perfect condition after a long series of test runs. A single and momentary trial of the armature without the choke-coils exhibited a superlative degree of sparking, as was to be expected.

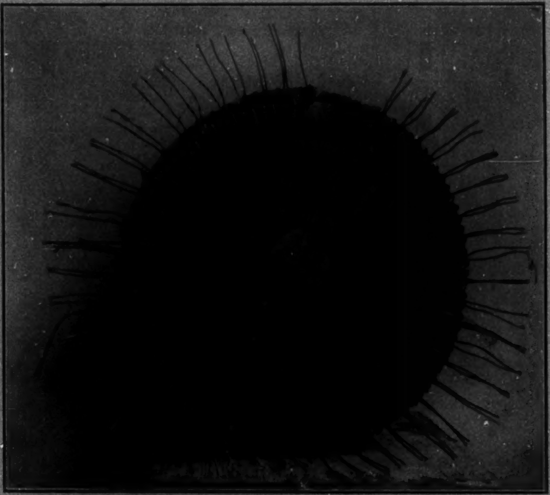


Fig. 5

The Inversion of Field and Armature in the Single-Phase Series Motor

In the direct-current motor the field should be much stronger magnetically than the armature and it should, therefore, be the external member to give room for the field windings; in the alternating-current commutator motor, however, the armature must be the preponderating member and it should, therefore, be the external member to give room for the armature windings. An internal-rotating-field external-stationary-armature type of direct-current dynamo was brought out a number of years ago in England, but this type of direct-current machine is now entirely discredited both practically and theoretically. The internal-field external-armature type of single-phase series motor, however, presents very great advantages as follows:

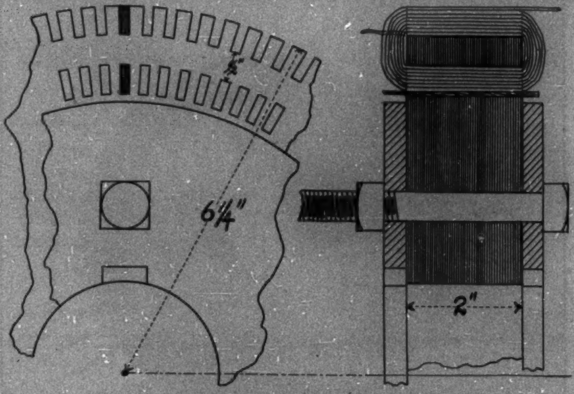


Fig. 6

(*a*) It presents more available space for the windings.

(*b*) It makes possible a material shortening of the end-connections of the compensating windings without lengthening the end-connections of the armature windings.

(*c*) It makes possible the removal of all non-sparking devices from the motor region proper, relieving the designer of every limitation in the use of resistance leads or other non-sparking devices except the limitation of cost and weight; and

(*d*) It makes possible the detaching of the commutator and the utilizating of the large amount of space ordinarily occupied by the commutator for motor iron and motor copper.

What may at first sight appear to be a disadvantage in the detaching of the commutator is the necessity of driving the brush mechanism by gearing, but the transmission of the power required for this purpose does not present a serious problem; indeed, it would seem that the advantage of having the commutator and brushes always in view and always easily accessible would counterbalance any mechanical disadvantage involved in the detaching of the commutator.

Figs. 9 and 10 represent sectional views of two single-phase series motors having the same external and internal dimensions. Fig. 9 represents the ordinary design with internal armature and external field, and Fig. 10 represents the new design with internal field and external armature. The following table exhibits the details of dimensions, weights, losses, and efficiencies of these two machines according to the designs of S. S. Seyfert, and according to the independent calculations of Comfort A. Adams of Harvard University, and of A. S. McAllister. The core loss in the armature is calculated in each case as if it were due to the full-load flux density at normal primary frequency. In fact, armature core losses are somewhat larger than this.

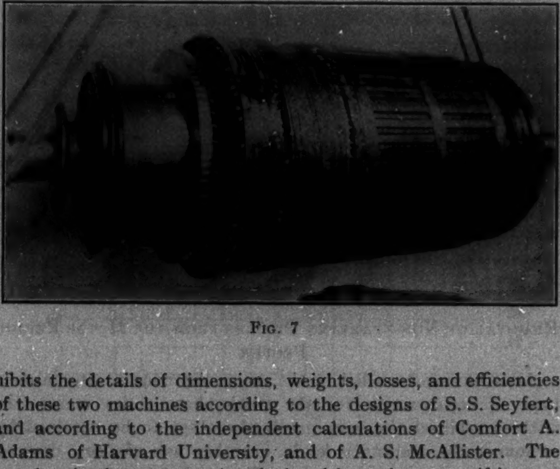


Fig. 7

These calculations are substantially in agreement, and they show a remarkable difference in rating of the two types of machine. The internal-field external-armature type of machine has a rating which is approximately 20 per cent in excess of the rating of the external-field internal-armature type of machine.

TABLE I

COMPARISON OF INTERNAL AND EXTERNAL FIELD SINGLE-PHASE MOTORS OF SAME SIZE

	Adams		McAllister		Seyfert	
	New type	Old type	New type	Old type	New type	Old type
Outside diameter, inches	30	30	30	30	30	30
Inside diameter, inches	10.75	10.75	10.75	10.75	10.75	10.75
Net length of iron	15.3	15.3	15.3	15.3	15.3	15.3
Full-load speed, rev. per min	550	583	550	576	550	576
Horse power at above speed	156.7	130.7	157.1	129.1	160.5	131.5
Efficiency at full load, per cent	88.4	89.5	89.9	89.5	91.1	89.8
Power-factor at full load, per cent	81.3	77.2	78.2	77.8	76.9	73.
Full-load current	432	432	432	432	432	432
Terminal electromotive force	372	327	387	318.5	386	330
Electromotive force between adjacent segments of commutator at brush	10	10	10	10	10	10
Weight of copper, total	894	824	888	850	881	846
Weight of copper per h.p	5.7	6.3	5.65	6.59	5.5	6.45
Weight of iron, total	1767	1781	1737	1659	1757	1742
Weight of iron per h.p	11.3	13.6	11.1	12.8	10.9	13.2
Total weight of active material	2661	2605	2626	2510	2639	2589
Total weight of active material per h.p	17	20	16.7	19.4	16.5	19.7

REMOVAL OF NON-SPARKING DEVICES FROM THE MOTOR REGION PROPER

After having been led to the external-armature internal-field type of construction for the single-phase series motor, the authors realized the very great advantage to be obtained by removing the resistance leads, or other non-sparking devices, from the motor region proper. These advantages are:

1. That resistance leads and balanced choke-coils, for example, can be used regardless of the amount of space they occupy so that the advantages to be gained by the use of such devices may be pushed to the limit, thus enabling the designer to produce a machine which commutates satisfactorily with a higher short-circuit voltage than would otherwise be possible.

2. The power losses in the non-sparking devices take place outside of the motor region proper and do not therefore have to be taken care of by ventilation.

3 Repairs to resistance leads, or other devices for preventing sparking, may be made with the greatest of ease and without opening up the motor in any way; and

4 Arrangements can be provided for the short-circuiting of any portion of the resistance leads or the disconnecting of the choke-coils at any prescribed motor speed, thus enabling the designer to treat the problem of starting and the problem of steady running independently of each other.

REMOVAL OF COMMUTATOR FROM MOTOR REGION PROPER

Another great advantage secured by the adoption of the external-armature internal-field type of construction is the possibility of removing the commutator from the motor region proper and the consequent possibility of utilizing the motor region solely for motor iron and motor copper. This change alone represents a possible increase of about 60 per cent in the motor rating that can be placed in the region occupied by the motors of the New York, New Haven and Hartford locomotives, and it has the further advantage that the commutator losses occur outside of the motor region proper, thus simplifying the problem of ventilation.

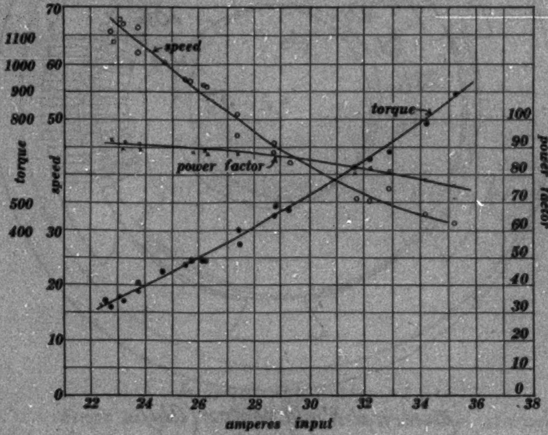
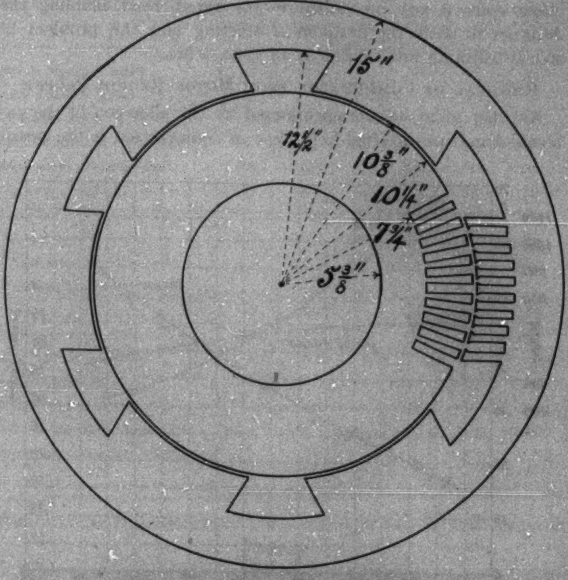


FIG. 8

A 500-H.P. DIRECT-CONNECTED, 25-CYCLE, SINGLE-PHASE SERIES MOTOR BETWEEN 62-INCH DRIVERS

The authors have worked out in succession the more important details of design of five single-phase series motors in their



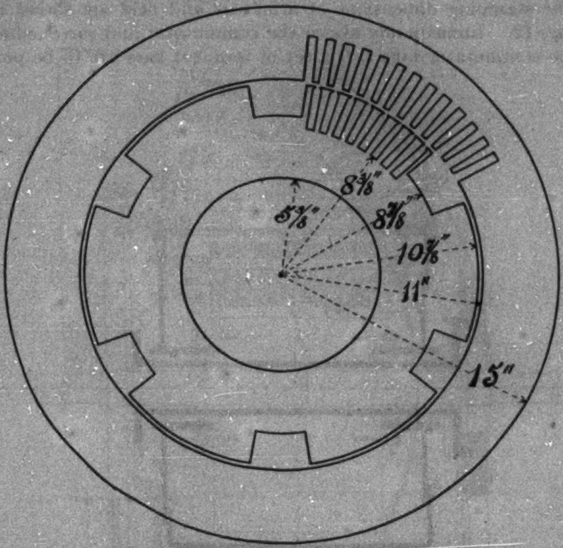
External Field Motor (Old)

Single air gap = 0.125"
% polar embrace = 70
No arm. slots 63
" field " per pole 8
Arm. slots ½" X 2½"
Field slots 7/16" X 2½"

Arm. winding simplex lap, 3 coils of 2 turns each per slot.
189 commutator segments.
(Seyfert's design)

FIG. 9

application to the principles set forth in this paper. The last of these studies in design related to a 25-cycle motor to be placed between 62-in. drivers on a standard gauge locomotive. This motor is referred to as motor No. 5. Fig. 11 is an outline sketch of this motor; *F F* is the internal rotating field and *R R* the collector rings for leading current into and out of the field and compensating windings; *Z Z* are the end-connections of the compensating windings, *A A* is the external stationary armature, *C C* the detached commutator, *S S* the rotating-brush arms which carry the brushes *B B*, and *R′ R′* the collector rings for supplying current to the rotating brushes. The axis of the com-



Internal Field Motor (New)

Single air gap = 0.125"
% polar embrace
No. arm. slots 80
" field slots 8 per pole
Arm. slots ½"×2½"
Field slots 7/16"×2½"

Arm. winding simplex lap, 3 coils of 2 turns each per slot.
240 commutator segments
(Seyfert's design)

FIG. 10

mutator is vertical, and the commutator is represented as being a hollow cylinder with the commutating surface on its interior. The brush shaft is supposed to be supported by arms which project forwards and backwards in the Fig. to the front and back parts of the motor casing; these supports are not shown in Fig. 11. The stamping dimensions of armature and field are shown in Fig. 12. Immediately above the commutator and surrounding the commutator lugs *L L* a set of terminal bars are to be provided to which the armature leads are to be connected, and the resistance leads and balanced choke-coils are to be connected between these terminal bars and the armature lugs and placed in any convenient position in the locomotive cab.

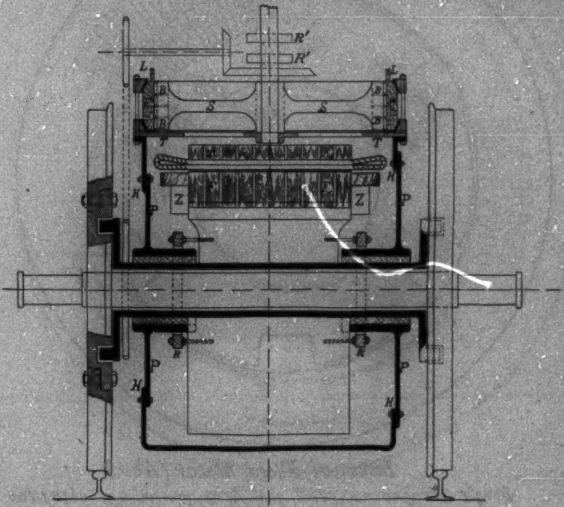


Fig. 11

Provision is made for removing the internal field for repairs by sliding it out endwise. The details of this arrangement are shown with sufficient clearness by the holes *H* in the two ends of the motor casing, and the plates *P* which cover these holes; the left-hand driver in Fig. 11, being provided with a detachable

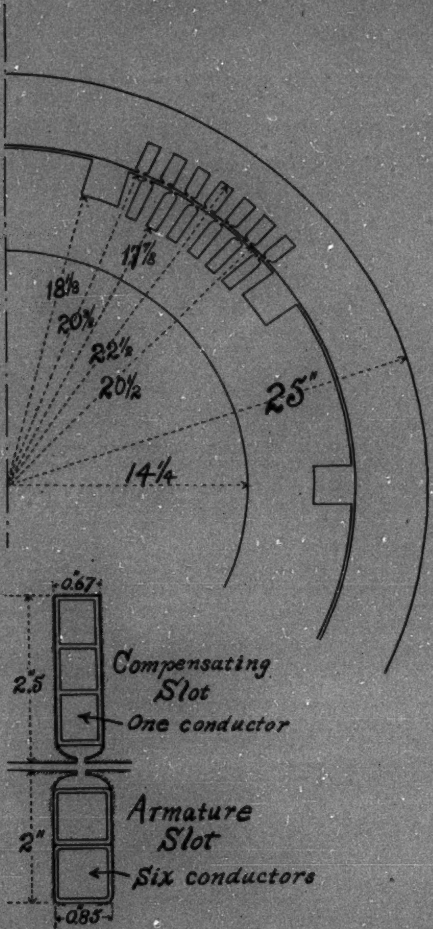

17⅞
18⅛
20¼
22½
20½
25"
14¼
0.67"
2.5"
Compensating Slot
One conductor
2"
Armature Slot
Six conductors
0.85"

Fig. 12

rim so that what remains of the driver when the rim is detached can pass through the armature of the motor.

It was decided to adopt a 10-pole field instead of a 12-pole field as in the present New Haven motors. This decision was reached on the basis of a conviction that satisfactory commutation can be accomplished with 12 volts between commutator bars at the brushes by the free use of non-sparking devices which is permitted by the internal-field external-armature type of construction.

The more important items of design of motor No. 5 are here collected to give a better idea of the machine.

TABLE II

Gross motor length, $39\frac{3}{16}$ in.
Net length of iron, 21.46 in., which leaves 12 in. for end-connections and for 9 ventilating ducts each $\frac{5}{8}$-in. wide.
Outside diameter of motor, 50 in.
Terminal voltage of motor at full load and 45 miles per hour, 216.7 volts.
Full-load current, 2400 amperes.
Counter electromotive force at full load and 45 miles per hour, 154.8 volts.
Mechanical power developed in armature at full load, 380 kw. or 509 h.p.
Power-factor at full load, 76.8 for air-gaps of $\frac{1}{4}$-in. total.
Power-factor at full load, 83.1 for air-gaps of $\frac{3}{16}$ in. total.
Armature copper loss, 6010 watts.
Field copper loss, 1655 watts.
Compensating copper loss, 5140 watts.
Field core loss, 5940 watts.
Armature core loss, 7746 watts (calculated for full frequency and full-load density).
Total stator loss, 13,756 watts.
Total rotor loss, 12,735 watts.
Total power dissipated in motor space, 26,491 watts.
Electrical efficiency, neglecting commutator losses, 0.937.
Voltage between commutator bars near brushes, 12 volts effective.
Commutation constant corresponding to effective value of full-load current, 0.947 (equals reaction electromotive force per armature section during reversal of current at commutation).
Armature winding duplex lap with 1008 inductors.

DISCUSSION ON "ON THE SPACE ECONOMY OF THE SINGLE-PHASE SERIES MOTOR." NEW YORK, JANUARY 14, 1910

S. M. Kintner: The topic of space economy of single-phase motors is a most timely one and merits a very complete discussion. In the paper presented this subject is dealt with in a very heroic manner, and the methods proposed for increased output are certainly radical in the extreme.

In the discussion of a paper presented by the theorist, with admittedly no practical experience, there is always the danger of too much stress being laid upon the fact that these are the ideal conditions, and that matters of detail in carrying out such a proposal are entirely subordinate and not worthy of serious discussion at such a time. In this paper, however, there are a number of details which deserve special attention, as it is largely upon these details that the success of the plan for increased output depends. A comparison of the output of the proposed 500-h. p. motor, that the authors submit as one that could be operated within the space limits of the present New York, New Haven and Hartford Ry. Co's. locomotive motors with one of those motors, shows that there is no gain in output per unit weight of active material, that is copper and laminated iron. The attempt to gain, has been made by dividing the motor up into two parts, one of which is made up of the magnetic circuit and inductors which occupies all of the available space at present used by the entire motor on the New Haven locomotives, and the other part, made up of the commutating device with its necessary choke coils for keeping down the short circuit currents, which the authors propose to place in some convenient location outside the motor frame, and which has its own additional space requirement.

With the proposition then that an increased output can be effected in direct proportion to the increase in active materials, such as copper and laminated iron, that can be placed in the available space, the discussion hinges on:

1. The feasibility of the external commutator with revolving brush holders, and,
2. The value of balanced choke coils for limiting the short circuit currents.

In passing, it may be well to note that, estimating the dimensions of the copper conductors from published I^2R losses, the insulation allowances in the proposed 500-h. p. motor are much too small, there being but one-half that allowed in the armature slots of standard machines, which allowance the experience of years has indicated as the minimum that is safe. Further, it should be noted that the method of getting the windings in place with the proposed slot, copper and insulation dimensions, is by no means evident. Again, the number of commutator bars selected is such as to cause some difficulty in connecting the equalizers.

There is also some question as to how successful the commutation would be.

My understanding of Prof. Franklin's duplex winding is, two independent parallel windings, in which there are 12 volts between alternating commutator bars, with one bar of the other winding intervening—am I correct in that?

W. S. Franklin: Yes, 12 volts with one turn of wire around the field flux.

S. M. Kintner: In my statement here, I have assumed that it was alternating commutator bars that were subjected to these 12 volts difference, and I am not clear just as to the type of windings proposed, if that is not the case. However, the same condition of total weights of metal, copper, iron, etc., holds as regards output, flux densities, etc.

I do not believe an external commutator with revolving brush-holders can be built for this class of service which will be a commercial success. The difficulties involved are:

1. The construction of the commutator with its 504 flexible connections from the motor windings, through the choke coils mounted on the locomotive cab, as proposed by the authors, down to the commutator bars.

2. The mechanical arrangement necessary for driving the brush-holders synchronously. This forms a problem in construction that has no feasible solution.

It seems to be well nigh impossible to devise a satisfactory arrangement of this kind when viewed from the standpoint of reliability, accessibility for inspection and repairs, freedom from mechanical injury during overhauling other parts of the locomotive, first cost, etc. Again the increased complication, cost and maintainance expense of the two sets of collector systems for supplying current to the brush-holders and to the rotating field, is another serious feature of this type of motor. While the authors' statement that but little power would be required to drive the rotating brush-holders is probably true, it does not necessarily follow that no serious difficulty is involved in the construction of such a drive. On the other hand, I believe it would be very difficult to construct a drive which would be absolutely positive and not liable to any interruption, and which would maintain accurately for long periods of time the correct brush-setting on the commutator. It is a well-known fact that single-phase commutator motors are very sensitive as regards brush-setting and great care is taken to insure a correct setting on the present types of such motors to within less than 1/16 in. as measured on the commutator face.

It is not at all likely that anything near this accuracy could be maintained with the proposed system. Fortunately, a limited amount of lost motion would be beneficial, as it would tend to rock the brushes backward for more favorable commutation. All the brush-holders if rotated at motor speeds would need to be carefully balanced and the carbon springs would require some form of compensator on account of centrifugal forces which would otherwise cause unequal brush pressures. Many other difficulties suggest themselves, but the foregoing are sufficient to indicate the character of trouble that would be encountered.

On considering the question of balanced choke-coils for limiting the magnitude of the short-circuit currents, one is surprised to find how large these coils become. It is worthy of note in connection with the 500-h. p. motor proposed by the authors, that the voltage between consecutive commutator bars is not as great as that on the New Haven motors. The magnetic density in the various parts of the proposed motor is also somewhat less than in the New Haven motor.

From this it may reasonably be argued that the size of the choke-coils and the motor power-factor proved to be the limiting conditions which prevented an increase in output per unit mass of material.

There are two other points that should be considered in connection with the choke-coils, as determining factors of their value:

1. Their ability to withstand without injury heavy momentary overloads, such as they might be subjected to in the event of the motor not turning over at once when current is applied at starting, and

2. The character of their construction combined with an adaptability for ready assembling in a suitable manner and at a reasonable cost.

In considering the first point, an examination of the choke-coil for the small machine shown in the paper, indicates that there is approximately as much resistance in the copper of the choke-coil as would ordinarily be used in a regular resistance lead, and that this alone would have been sufficient to limit the short-circuit current without the inductive effect. This then indicates a serious sacrifice in sturdiness and overload capacity in order to keep down the size to such proportions as would allow the choke-coils to be mounted inside the armature. In this case there has been increased complications, equal or greater loss, an inferior arrangement to withstand heavy overloads, and when compared wth the resistance lead properly installed, it seems to be less desirable than the latter.

The authors state "It does not seem possible, however, to produce a single-phase motor that will operate satisfactorily without the use of special devices for the prevention of excessive short-circuit currents."

I wish to take exception to this statement, as it *is* perfectly feasible to build motors without any special devices of this nature, provided the induction per pole is kept low enough. There are a great number of motors of this kind in operation giving satisfactory service. The contact resistance of the carbon brush is sufficient to limit the current to a safe value provided the short-circuit voltage does not exceed 3½ to 4 volts. The employment of preventive leads, however, allows the use of higher inductions per pole, and in general results in a somewhat smaller motor for the same rating.

Considering the second point, that of cost and adaptability for assembling, I have found on calculating suitable coils for the proposed 500-h. p. motor mentioned in the paper, that the sizes are rather startling, and one is inclined to the belief that the authors were so glad to find a place large enough to accommodate the choke-coils that the mechanical difficulties involved in the use of the external commutator looked small.

Space economy. The space available for the motor of a locomotive depends so much on the type of motor-mounting and drive, that comparisons on the basis of output of the motor designs of different types are misleading. It is of course allowable and proper, to compare locomotive performances provided they have been designed for the same class of service.

For motors mounted concentric with the locomotive axle similar to the New Haven motors, the desired freedom and standard wheel-flange-spacing fix the maximum length of motor, while the motor diameter allowable, depends upon the wheel size and the permissible clearance below the motor.

If a particular locomotive speed condition is assumed, the end clearances will be practically the same, and the size of motor that can be put in the space will increase with the increase in the driver size. For a particular case of this type of mounting, in which the same locomotive speeds are assumed for various sizes of drivers, the increase in horse power output, which can be put in the available space, will be approximately along a straight line, which indicates a 250-h. p. motor on 62-in. drivers and a 500-h. p. motor on 94-in. drivers.

The increase in motor weights will be somewhat more rapid than their increase in diameters, owing to the fact that the active electrical and magnetic parts will increase almost directly with the diameters, while the weight of most of the mechanical parts will increase more nearly as the square of the motor diameter.

Motors mounted horizontally, with one side supported rigidly on the axle, similar to the ordinary method of mounting motors on car trucks, gradually lose end-room as their sizes increase, on account of mechanical requirements of increasing space for larger gears, and their outputs do not work out on so simple a curve as the motors mounted concentric with the axles. This loss in end-room results in a double loss as it makes it necessary, for a given rating, to use a larger motor diameter. This increase in motor diameter requires a reduction in motor revolutions, on account of mechanical limitations, which in itself makes a larger diameter necessary. This increase in armature diameter, forces the gear centers further apart and increases the size of gears. A final balance is reached, above which, it is not feasible to mount motors in this manner on account of the gear sizes and dead motor weight on the axle. This dead weight can be relieved by the use of quills which afford a spring support for the motor, and this makes it possible to increase the size of motor. The use of a quill, however, increases the gear centers, and this causes the limit due to the size of gear, to be reached sooner. Here it should be noted that the required range of locomotive speed plays an important part. The motor, for mechanical and insulation reasons, is designed for a certain limiting speed above which it must not be operated. If the continuous rating speed is chosen near or at the maximum speed, the smallest motor possible for the locomotive rating is obtained. As the continuous rating speed is decreased, the motor size increases. It follows, therefore, that from the standpoint of the motor design alone, the less the requirements of range in locomotive speed between continuous and maximum, the cheaper the motor will be. It is largely on this account, coupled with the mechanical requirements of locomotive riding qualities at high speeds, that locomotive costs are increased so much, for conditions where it is expected to operate in both freight and passenger service at quite different speeds. In general for this type of mounting, there is little or no gain in motor size by reducing the continuous rating locomotive speed below about 12 miles per hour.

Motors mounted directly above the axles and geared thereto through quills, are but one division of this general class of direct-gear drive and are subject to the same limiting conditions. The quill is, however, necessary in all cases with this type of mounting in order to relieve the axles, wheels and track, of the otherwise excessive dead weight.

When use is made of the combination drive employing gears and side rods, there is a distinct gain in the end-room space available for the motor, as in this type of drive, the entire space between the locomotive side-frames, which are generally plate-frames inside the wheel-flanges, can be utilized for the motor. The gears can be placed outside the wheels and there is not very much difficulty in making them any desired size. The driver sizes, wheel-base limits, and crank-throw are, in most cases, the determining factors. This increase in end-room makes a smaller diameter and higher speed motor possible, and hence a cheaper motor. This type of mounting gives almost as much end-room as that employing the straight side-rod drive. The latter has a slight advantage as it is possible with it to extend the motor up to the wheel-flanges and in fact to cut away part of the motor housing for a still further slight gain.

With both of these types of drive the diameter of the motor is limited by cab clearances. These last mentioned types of mounting, allow space that makes possible the largest sizes of motors desirable.

The combination drive is much more flexible and gives a better selection of motor speeds and driver sizes, as the gears can be selected to get the desired locomotive speed. It is impossible with these last mentioned types of drive, to state the sizes of motor in terms of the ordinary methods of rating, without a definite limiting speed range, and so I will not attempt to state more than the preceding indications of the general limits.

E. H. Anderson: The paper brings out very clearly the difficulties of designing a single-phase commutator motor. The scheme of placing reactances in such connection as to theoretically reduce sparking is ingenious, to say the least. The criticism of the scheme is, that it does not make for simplicity. The simplest form of apparatus is more often the most enduring.

It appears from the text that the leads of the stationary winding are connected into the stationary commutator, although space and detail of construction are not shown. In order to take the motor apart for repairs, it is necessary to pull off a driving-wheel, or separate the stationary member, and in this case it becomes necessary to disconnect the winding and all the commutator leads coming from the lower half. The driving mechanism for the revolving brush-holders must be positive and rigid. No slack or looseness can be allowed, for the exact position of the brushes on a single-phase commutator motor is very essential for proper operation and speed. Such a motor as described, usually has about an 8-in. commutator and 18 in. of core iron between heads.

The power of a motor is dependent largely upon the length of core, and if all of the commutator length could be put into core, that is, by adding 8 in. to 18 in., it becomes possible to increase the power about 45 per cent. However, all the commutator length cannot be added to the core, for the reason that there must be a circular conduit at each end to allow the leads of the lower portion of the stationary member to be brought up to the stationary commutator. This will require approximately 3 in. on each end thus leaving 2 in. to be added to the core-length, giving 20 in. instead of 18 in., or an increase of 11 per cent. After the leads leave the conduit they must be spread around the commutator and held firmly, as well as properly ventilated. Usually from a given space, a certain amount of heat can be blown out, so that with a given efficiency only a given amount of work can be done in that space. The driving device for the revolving brush-holder rigging must take up some space on the axle. This will no doubt use up the spare 2 in. with the result that the iron core between heads is not increased.

The question naturally arises, is the taking away the commutator from the rotary member, and placing the same on the stator worth the complication? It appears from the paper that this scheme is best suited for single-phase axle motors for locomotives, and is limited to the construction shown, of mounting the stationary member on a quill and using quill-drive. It appears that there is difficulty in building within the limited space between wheels, a motor large enough to slip the wheels and do the work usually required on the usual axle weight of 50,000 lb. The above refers to a single-phase commutator motor and this scheme with its complication is an effort to increase the size of motor.

The serious question about the construction, to my mind, is that it is not the simplest. A prominent railway company built and installed a motor on a single-truck car, which should act as a counterweight to the real motor. The motor was a chunk of cast-iron, with armature bearings on it, mounted outward on a single-truck car, and over-balanced the effect of the real motor, which was outwardly-hung on a single-truck car. This was put on as it was thought the real motor might tip up end wise and block the system. These motors were used for a long time, and gave no trouble, probably on account of their simplicity.

E. F. W. Alexanderson: The title of the paper opens a broad subject. There may be as many ways to look at it, as there are designers who have worked on the development of single-phase railway motors. I prefer to look at the subject in a somewhat different light rather than discuss the schemes presented in the paper.

In the design of any electrical apparatus, there is usually one requirement that is more severe than any of the rest, or one weakness in the type of apparatus considered to which most of the attention must be given, so that all the other features must be subordinate to that particular consideration. Most electrical machines are sold on the basis of a standardized commercial rating, and this rating is in most cases based upon the temperature rise during a certain test. Other features, like regulation, power-factor, efficiency, and overload capacity, are given as supplementary descriptions of the apparatus. The commercial rating of railway motors is based upon heating, usually upon the one-hour test at 75 degrees rise, and the adaptability of a railway motor to any specific requirement is usually judged by the heating of the motor. This generally accepted method for determining the service capacity of railway motors has been developed with reference to the motor of the wholly enclosed type.

The three principal limitations in the design of an alternating-current railway motor are heating, commutation, and starting torque; of these three, the starting torque is, however, the most important.

The first attempts to design the alternating-current railway motors were naturally along the same lines as those of the direct-current motors. The motors were completely enclosed, and the service capacity was determined from the heating characteristics. It was soon found, however, that owing to the lower efficiency of the single-phase motor, the temperature has a tendency to become considerably higher than in the direct-current motor. An increase in the size of the motor, in order to reduce the temperature, led to an increase in the weight of the trucks, car-body, and the control, so that the motors had to do more work than was contemplated in the first place, and the desired reduction in heating was not obtained. At present it is accepted as a necessity by all manufacturers of alternating-current railway apparatus, that the motors must be cooled, either by natural or forced ventilation. As soon as forced ventilation is adopted in an alternating-current motor, the whole basis of the design is changed: The cooling that can be accomplished in this way is so effective, that heating is no longer the limiting feature of the design. Commutation difficulties can be entirely overcome at any normal operating speed, by application of a commutating field of suitable phase and strength. They can also be counteracted, to a great extent by the use of so-called resistance or preventive leads. The ruling feature is therefore the starting torque. This applies to the three-phase railway motor, as well as to the single-phase railway motor, although for entirely different reasons.

In the discussion of Dr. Hutchinson's paper on the Great Northern electrification, I explained that the reason why the three-phase motors exceeded their guaranteed capacity on the basis of temperature rise, with forced ventilation was not an accident. The starting torque was the most severe requirement, and as a matter of fact, the motors are able to slip the wheels of the locomotive, only with a necessarily small margin.

In the single-phase railway motor, the starting torque is limited by local heating on the brushes, commutator bars, and certain parts of the winding. Various methods have been devised to increase the starting torque of the single-phase commutator motors as much as possible. Although there may be a disagreement as to what methods are the most practical it seems to be a general agreement that some special methods must be used.

The starting torque of the single-phase commutator motor is limited by the voltage per bar on the commutator, and the current per bar in the winding. Generally speaking, it can therefore be said that the starting torque is proportional to the size of the commutator. The special methods that are used to increase the starting torque consist in providing means for either raising the voltage per bar or by means for raising the current per bar. In other words, both systems require space in the motor which could otherwise be usefully employed if the motor was intended for direct current.

The scheme presented by the authors of the paper is the first of the two mentioned principles for increasing the starting torque, carried to the extreme. The system is, according to the authors, very effective, but there is also every indication that it takes room in proportion to its effectiveness, and there is no convincing evidence in the paper that the space occupied by the motor with its elaborate non-sparking devices, will not be quite as large as the space of a motor of more familiar design.

This refers to the motor of the Seyfert type with rotating commutator shown in the illustration. The scheme of the detached commutator, apart from its complication, does not solve the problem of space factor as it is worked out in the design shown in the paper, because no provisions have been made for materially increasing the diameter of the commutator, which after all is a measurement of the starting torque. A natural solution is however given by the use of side rods which allows the commutator as well as the rest of the motor to assume its necessary dimensions as well as its natural proportions.

It is interesting to observe that the results obtained by the four or five manufacturers of single-phase railway motors in America and in Europe, agree closely in regard to weight and space per horse power. In order to give some more concrete figures, as to the space and weight factor of moderate size single-phase motors, the following data may be mentioned. A 25-cycle motor of the series repulsion type designed for 36-in. wheels, has a weight of 5900 lb., and delivers 150 h. p. at 600 rev. per min. in accordance with standard rating. This is, as far as I can see, in close agreement with recent developments of motors of several other types and makes.

The various schemes employed for overcoming commutation difficulties cannot, therefore, be judged by the space factor or the weight per horse power. The nearest to a practical comparison is undoubtedly a test that has been embodied in the specifications for locomotives in connection with the contemplated electrification of two of the large western railroads, that the motor should be able to develop full torque at stand still for a specified time, one minute or five minutes. If the motors are compared on a basis like this, the type will undoubtedly be most favored, which offers the greatest simplicity of structure, and the easiest work for the repair man.

S. S. Seyfert: The discussion that has taken place, following this paper, has amply repaid us for going to the trouble of presenting a few ideas in the line of motor design. Perhaps the best reason for bringing up a subject like this is to find out what the chief workers are doing.

I would like to mention a few points, however, because it seemed to me during the discussion, that the non-sparking devices that are proposed were assumed to be a necessary part of the inversion of the relative positions of field and armature. It is not necessary to use these choke-coils in the case of a motor with external armature, and as a matter of fact I have often thought that it might be desirable to use resistance leads, only under certain circumstances, especially if the short-circuit volts are reasonably small. We have found it is extremely difficult to design a motor of so large size, with a reasonable short-circuit voltage per turn, for with a reasonable number of poles, say 12, the flux per pole on a 500-h.p. motor becomes so large as to produce 12 volts or more per turn on the armature circuit, and if we wish to reduce this voltage we would either have to tap into the half-turns or increase the number of poles.

In order to build a large single-phase motor, it is absolutely necessary to use a large number of poles, or use a high short-circuit voltage per turn. I think however, that motors could be built on the resistance-lead principle, that would commutate well enough, and in that case the stationary character of the armature, with the available space for placing the leads, would enable us to design the leads somewhat more generously, and therefore their liability to burn out at starting would be less, which would mean a lessening in the cost of repairs and an increase in the reliability of service. I think it is plain, that with the ordinary construction of armature, in which the resistance leads are doubled upon themselves in the bottoms of the armature slots, they consume a large amount of valuable space, real motor space, and they add their heating to the total heating of the armature. In case of burn-outs, which are liable to occur at starting, the armature windings have to be undone to repair the leads. In this case, I can easily imagine an arrangement of the leads so that they might be replaced at short notice separately and in fact a lead might be replaced while the motor was running, if the winding of the armature was of the proper type. On the basis of resistance leads alone, dropping entirely the question of choke-coils, it would seem an advantage to have the leads so located, that they can be easily and separately repaired. This would compensate for a great deal of the otherwise complicated arrangement.

I would say another word about the length of commutator. One of the members who discussed the paper mentioned that the length of the commutator on the present New Haven motor was about seven or eight inches, and in case of the removal of this commutator we would gain that space. I find, if we attempt to build a 500-h. p. motor, that the commutator would be about a foot long. In this case, assuming the commutator on the motor concentric with the axle, we would gain a foot of space by removing the commutator. Should we decide to make the commutator concentric with the armature—this one foot of space needed would force us to a greater driving-wheel diameter. It should be plain, therefore, that the increase in gross length of useful iron made possible by the removal of the commutator would be 12 inches instead of the seven or eight inches, as would be the case in changing a 250-h. p. motor. We were driven to that construction to get the necessary rating on a direct-connected motor for 62-in. drivers.

As to design, the inverted motor has among others, the following advantages:

1. The long external yoke or armature core has to carry the effective armature flux only, whereas, in the old type of motor, the corresponding core has to carry the total field flux.

2. The placing of the armature externally allows the use of a wider and shallower armature slot, resulting in a better commutation constant and a slightly better power-factor. The compensating slots through the poles must be deeper in this case, which condition may be easily met. Because of the comparatively low voltages at which single-phase motors must operate, it has

been found somewhat difficult to satisfy the direct-current commutating condition on a motor of large size with such a small number of poles.

3. The air-gap periphery is somewhat increased in the case of the external armature motor mainly because the armature requires less radical depth than the field.

4. The end-windings of the compensating-coils are very much shorter, as was mentioned in the paper.

We made some experiments on core losses in field and armature,

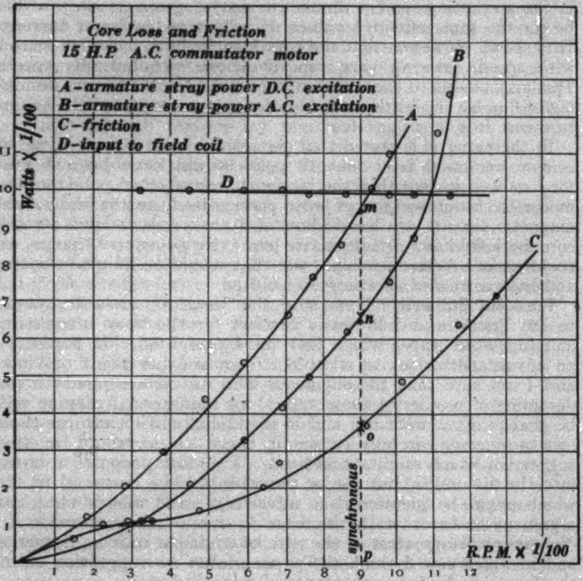


FIG. 13

which might be interesting at this juncture. For some time Dr. Franklin and myself were under the impression that the core losses per unit of volume in the armature of the alternating-current motor should diminish as synchronous speed is reached. Upon going into the theory of the matter this seems to be so, but for some reason, the core losses actually increase somewhat with speed. The experiment was performed on a single-phase motor of the ordinary type, and the results are shown in Fig. 13.

In the first place, a constant direct current of 30 amperes was supplied to the field. The armature was rotated at a series of speeds up to and beyond synchronous speed.

Curve *A* gives the total input to the rotating armature from the driving motor; curve *C* gives friction loss in the motor tested so that *m o* represents the core loss in the armature.

In the second place a constant alternating current of 30 amperes effective value was supplied to the field. Curve *B* gives the corresponding core loss as measured by the driving motor. Curve *D* shows the watts input to the field-coil throughout the test. These curves show that the armature core losses in the aternating-current motor are not as great as they would be for the same effective values of induction on direct current. It is shown, however, that the core loss, in both cases, increases with speed, growing very rapidly above synchronous speed. This may be due to the fact that the losses caused by the bunching of flux by the teeth are such a large percentage of the armature core loss.

In the paper it is stated that we selected the 10-pole type of motor; we found later that 12 poles would have been better for it is well known that the larger the number of poles on the motor, the less its weight per horse power, because the individual magnetic circuits are less bulky, and the cross-sections of the core, both field and armature, are less. By going to 12 poles we could make a better machine, one that would commutate better and have a smaller short-circuit voltage.

President Stillwell: I am sure the Institute owes its thanks to Dr. Franklin and Professor Seyfert for the very interesting and suggestive paper which they have presented. It is always an advantage to look at a subject from another point of view, and I am sure that the engineers who are accustomed to the designing of motors of these types for commercial service will be glad to agree with me, and in a judicial spirit examine their own work very carefully to see if there be anything in this suggestion which might be utilized. I do not propose to enter into the discussion, but one or two points have occurred to me which might be mentioned to advantage, and one is that the argument in favor of the increase in output in proportion to dimensions are greatest in the case of multiple unit equipment, and in which case I think the paper makes no suggestion as to the location of the commutator and its leads.

In the case of the electric locomotive, taking the state of the art as it existed when the New Haven locomotives were designed, the designers were undoubtedly cramped for room in attempting to place the motors underneath the floor of the locomotive, but the tendency is now, I understand, rather towards raising the motors and gearing to a shaft, in which case the argument in favor of separate commutator and its leads from the field armature is somewhat minimized. I will now call upon Dr. Franklin to close the discussion.

W. S. Franklin: In regard to the location of the detached commutator in the multiple-unit car I may say that Professor

Seyfert and I have considered that matter in some detail after a consultation with Messrs. Gibbs and Hill, and we came to the conclusion that a very great advantage would be realized by placing the motor on one side of the axle, and the commutator on the other side of the same axle, taking the commutator leads across through a covered passageway over or under the axle.

In regard to the general question of detaching a commutator, I wish you to consider what a commutator really is. A commutator is a switchboard, and it is proper to detach a switchboard from the machine which it controls. I never saw a power house with a switchboard placed inside of the dynamo! I only make use of this evidently exaggerated statement in order to emphasize the fact that we have perhaps become too much accustomed to a certain point of view. Perhaps, after all, the detached commutator is the rational and practical thing, and yet I have enough respect for practical engineering to know that the question must ultimately be answered in practice. I do not know for certain whether the detached commutator is the best thing, and neither does anybody else know. It is a question which can be decided only by an actual and long-continued trial under practical conditions.

In regard to the importance of simplicity which has been emphasized by Mr. Anderson, I wish to point out that the motor which Professor Seyfert and I have designed is about the nearest approximation that I know of to a " piece of cast-iron."

In answer to Professor Kintner's question concerning the short-circuit voltage I would say that the short-circuit voltage of our No. 5 (500-h.p.) motor is 12 volts per turn, that is, 12 volts in a single turn around the field-pole.

The question was raised as to the necessary size or carrying capacity of the individual choke-coils. Concerning this point, it is stated in the paper that a short-circuiting arrangement can be provided so that choke-coils or resistance leads can be cut out or in at pleasure. The frequency of commutation is low at starting, and under these conditions one needs high resistance in the leads, whereas the inductive choking is rather small. At high speed, on the other hand, the choke-coils are extremely effective without any resistance. Therefore at starting, very high resistances might be inserted in the leads and these resistances might be cut out with increase of speed after starting.

I wish particularly to emphasize a point which is brought out in the paper, namely, that one of the most important features in the suggested design is, that you can treat the problem of starting and the problem of running as two distinct and separate problems; you can put large resistance in your leads at starting, and when the machine reaches a certain definite speed you can cut out as much resistance as you please by a ring which is made to drop between terminal bars in a manner which will at once occur to any designer.

A paper presented at the 243d meeting of the American Institute of Electrical Engineers, New York, February 11, 1910.

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A MODERN AUTOMATIC TELEPHONE APPARATUS

BY W. LEE CAMPBELL

The writer presented a paper before the annual convention of the Institute in 1908, dealing with automatic telephone equipment from an economic viewpoint.* The present paper will therefore be principally devoted to a description of the apparatus used and its method of operation in modern plants. Although there are several different types of automatic telephone equipment upon the market or being developed, practically all of the working plants use apparatus of the "Strowger" type with or without the addition of Keith line switches. Since this paper must be confined to one system, only the one which is extensively used will be discussed. The description will begin with a short reference to the subscriber's station equipment.

Prior to the year 1896, an automatic telephone subscriber called any number which he might desire by pressing push-buttons on his telephone. There were generally three push-buttons arranged and labeled as shown in Fig. 1. If the subscriber wished to call No. **143**, for example, he would first push the "hundreds" button once, then the "tens" button four times, and finally the "units" button three times. While this arrangement gave passable service, the subscribers made many mistakes in counting the pushes and sometimes did not press a button in far enough or hold it in long enough. Consequently, in 1896, a button-pushing machine or a "calling device", as it is commonly named, was substituted for the push-buttons. A modern wall telephone equipped with a calling device is shown in Fig. 2 and a modern desk telephone in Fig. 3.

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* A Study of Multioffice Automatic Switchboard Telephone Systems, Transactions A. I. E. E., 1908, p. 503.

As shown in these Figs. the visible portion of the calling device consists of a dial pivoted at its center so that it may be turned in a clockwise direction. For convenience in turning it has finger holes eleven in number around its outer edge. Through each finger hole, except the eleventh one, a number is seen. These numbers are consecutive from **1** to **9** and back of the tenth finger hole **0** appears. In automatic practice **0** always represents 10.

To call **143**, for example, a subscriber will first put his finger into the hole through which number **1** is seen and pull the dial around until his finger strikes the stop. He will then take out his finger and place it in the hole through which **4** is seen and again pull the dial around until his finger strikes the stop. Finally he will place his finger in the hole through which number **3** is visible and turn the dial till his finger again strikes the stop. He then places the receiver to his ear and awaits the answer of the party called. Each turn of the dial requires approximately one second, and by the time he has placed the receiver to his ear the automatic machines at central office will have completed the connection to the desired line and will be automatically ringing the bells of the desired telephone. When through talking, he hangs the receiver on the switch-hook and the break in the talking circuit thus made causes the central office apparatus to return to normal condition.

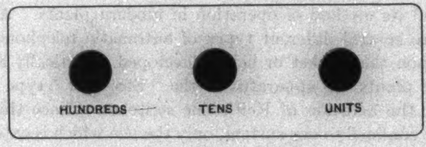


FIG. 1

There is contained within the calling device, but not seen, a revolving cam arranged to make and break the contact between a pair of springs. An escapement geared to a small governor controls the speed at which the cam revolves. The power is furnished by a clock-spring which is rewound each time the subscriber turns the dial. The cam does its work after the subscriber's finger strikes the stop and while he is placing his finger in the next hole. If he tries to turn the dial before the cam rotation is finished, he finds it locked. It stays locked until the cam rotation is completed.

The principles involved in the operation of the dial are carefully worked out and are essential to rapid and accurate calling; the finger is each time placed in a stationary hole in front of a stationary number and is then moved until its strikes a stop. Every movement is positive and accurate, regardless of the speed at which it is made. Any one who has experienced the slow and painstaking care required to manipulate the dial on an ordinary office safe to bring each successive number opposite the stopping point without first passing it, will readily appreciate that any calling device which would require the subscriber to stop each number opposite a pointer or, vice-versa, to stop a pointer opposite each number, would be very slow and inaccurate in comparison with a calling device like that shown in the illustrations.

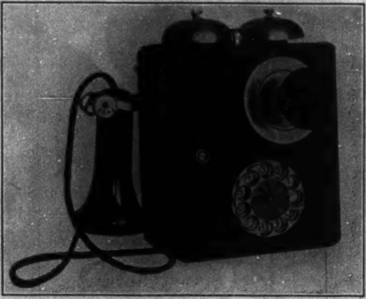


FIG. 2

If the number called by a subscriber is "busy", his receiver will give forth an intermittent buzzing sound, the same as that used for a busy signal in large manual systems.

If the number he calls is that of a former subscriber, or of a subscriber whose number has been changed, he will be automatically switched to the information operator, who will give him the information most suitable under the circumstances.

If a "long-distance" connection is desired, the subscriber turns his dial once from the 0 finger hole, which is labeled "Long-Distance" also. He is thereby connected directly to the recording operator of the long-distance board, who takes his order just as in manual practice and then informs him that she will call him when she has his party. When the long-distance connection has been put up, the operator calls the subscriber and the conversation proceeds in the usual way.

Each automatic system is generally equipped with an information and a complaint desk, each of which is presided over by an operator who supplies needed information to inquiring patrons, or records their complaints.

Extension telephones, coin-in-the-slot telephones, party lines, inter-communicating systems, and private branch-exchanges are all worked satisfactorily at the subscriber's stations.

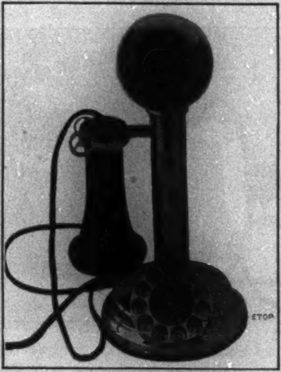


Fig. 3

A subscriber's private branch switchboard may be either of the well known manual type presided over by an operator—who makes the local connections and who supervises all of the calls to and from the public exchange—or it may be automatic with all subscribers' stations equipped with automatic telephones so that they may call each other or call public exchange patrons by means of their automatic calling devices without the aid of an operator, or it may be a combination of the two with the local calls automatic and those to and from the public exchange supervised.

It is perhaps needless to say that the transmitter, receiver, ringer, and hook-switch for an automatic telephone may be of any standard type. The only part of the instrument that is peculiar to the automatic system is the calling device. In fact an ordinary common-battery manual telephone may readily be adapted for automatic service by mounting the calling device upon it as shown in Fig. 4.

Turning from the discussion of the subscriber's station to the central office equipment, the machines which make the connections between subscribers' lines are divided into the following classes:

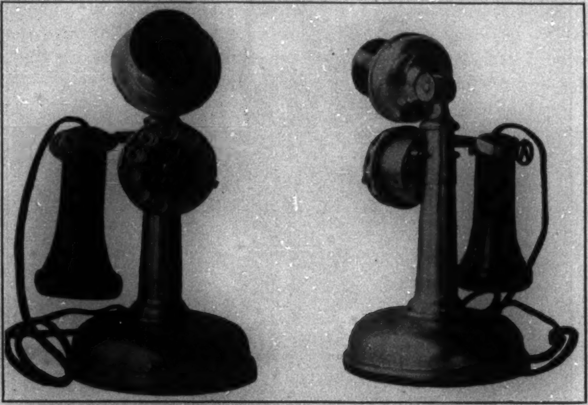


FIG. 4

1. Line switches.
2. Selector switches.
3. Connector switches.

A connector switch commonly called a " connector ", is the last one operated in completing each connection; but as its functions correspond most closely to those of an operator on a manual switchboard it will be considered first.

There are two principal differences between the work of an operator on a multiple switchboard and that of an automatic connector. The first lies in the difference in the number of lines to which they have access. The operator has within her reach a multiple jack for every line in the switchboard, be the number of lines 1000 or 10,000. She may therefore make a connection *to* any line entering the office, but a connector switch has access to but 100 lines. Secondly, a subscriber's operator takes the orders of and makes connections *for* certain predetermined subscribers only. The number she serves seldom exceeds 200 and is often less than 100, but a connector switch is, when idle, ready to handle the order of any subscriber who may wish to connect to any one of the 100 lines to which it has access.

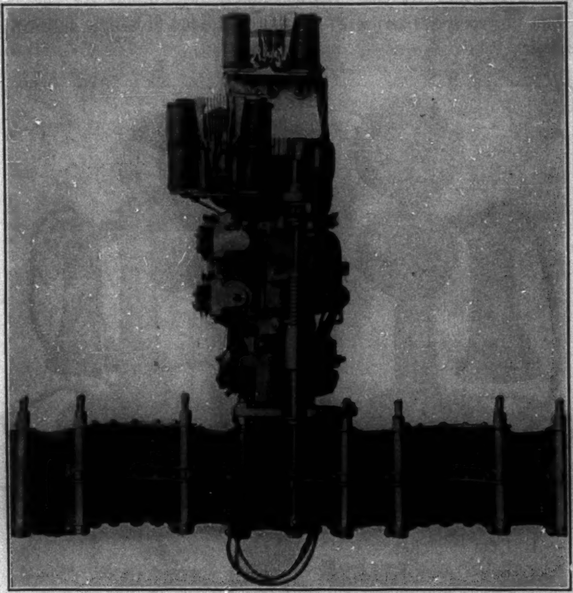


FIG. 5

A picture of a connector switch is shown in Fig. 5. The lower part of the machine supports two curved banks of contact plates or strips. The under bank, called the line bank, contains 100 pairs of these contact plates arranged in 10 horizontal rows, 10 pairs to the row. See left hand bank, Fig. 6. These pairs of bank contacts correspond to the line springs in the multiple jacks of a manual board, and, as pictured in Fig. 5, may be multipled before any desired number of connector switches. The upper bank contains 100 single contacts which correspond to the sleeves of multiple jacks. This is the busy-test bank, commonly called the "private" bank. The cord and plug of the manual board are represented by the "wipers" on the shaft of the machine. The lower or line wiper consists, as shown more clearly in Fig. 7, of a pair of long flexible springs insulated from each other and each soldered to a flexible cord, while the upper or private wiper is a pair of springs connected together to a third cord. The movements of the wipers, corresponding to those of an operator raising a plug and inserting it into the proper multiple jack, are performed by the shaft which has a step-by-step vertical movement and a step-by-step rotary movement.

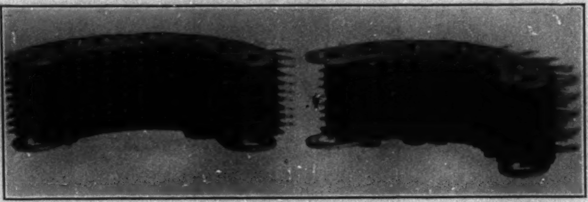


Fig. 6

These movements are actuated by pawls and ratchets operated by electromagnets controlled by the subscriber from the calling device on his telephone, and are always in accordance with the last two digits of the number he calls. For example, if he calls a number ending in **43**, the shaft is raised four steps and then rotated three steps, thus raising each wiper opposite the fourth row of contacts from the bottom of its respective bank and then sliding it over to the third contact in the row. The machine is then ready to close the circuit of the calling subscriber through to the circuit of the called party, but before doing this it first closes the private wiper-circuit only and thus makes an automatic busy test. If it finds the desired line busy, it keeps the connection open and immediately transmits the busy signal back to the calling subscriber. If the desired line is not engaged, the connector switch immediately begins to ring the called party's telephone bell automatically and intermittently. When he answers, the ringing stops and the two subscribers lines are closed together for conversation. Talking current is supplied to the transmitters of both telephones from the central office battery through the relay coils of this connector switch, just as in manual practice it is supplied through the relay coils of the cord circuit. The talking circuit includes nothing but these coils and the subscribers' stations. Its simplicity and perfect balance are shown by the circuit in Fig. 8.

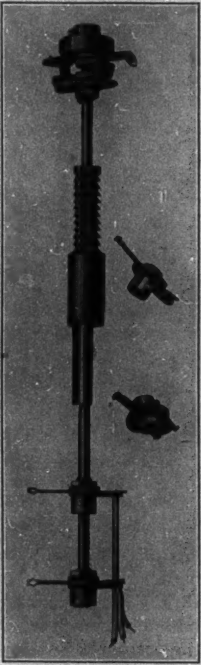


FIG. 7

When the subscriber's conversation is completed and the calling party restores his receiver to the switch-hook, the shaft of this connector switch is " released " and is immediately returned to normal position by means of a clock-spring and gravity. It is now ready to handle another connection for any subscriber in the plant.

One such switch cannot, of course, handle all calls to the 100 lines to which it has access. In the average plant, 10 connectors are sufficient, however, for each 100 lines, because ordinarily not more than 10 subscribers in any hundred are ever receiving calls simultaneously. Consequently a system of 10,000 lines, for example, is divided into 100 groups of 100 lines each, the calls to the subscribers in each group being completed by a set or multiple of 10 connector switches. Where it is found necessary, more than 10 connectors may be put in a multiple; where expedient, economy is attained by putting in less than 10. Uniformity is desirable, however, and it is therefore good practice—although it is not general practice—to exercise some care in arranging the subscribers' numbers, so that each group of 100 will contain approximately the same proportion of frequently used lines to lines that are used less often. The grouping of lines is strictly according to number; that is, all lines numbered from 2100 to 2199 are put into one group and connected to by one set of connectors, while all lines from 2200 to 2299 are put into another group, etc. It will now be understood that a calling party, to complete a connection to a desired line, must first obtain connection to an idle connector switch belonging to the group or multiple in which the desired line terminates. In other words, processes of group selection and of idle switch selection are performed by other switches which do their work before the connector switch is operated.

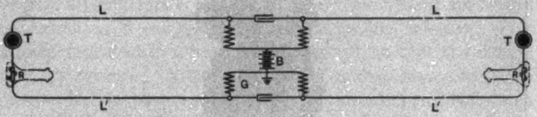


FIG. 8

These switches, which are called selector switches, have already been mentioned. A picture of a selector switch is shown in Fig. 9. It looks, and is, very much like a connector switch; in fact the mechanism and banks are the same. The differences are in the circuits and relays only. In a system of 10,000 lines, these selectors are divided into two classes; namely, first selectors and second selectors. While there is a group of connector switches for each 100 lines to which connections are to be made, there is a group or multiple of second selectors for each 1000 lines to which connections are to be made, and a group or multiple of first selectors for each 10,000 lines to which connections are to be made. The bank contacts of the selector switches are terminals of trunk lines instead of subscribers' lines. The first or lower row of first-selector bank contacts constitutes the terminals for a group of 10 trunk lines leading to second-selector switches in the **1000** section of the plant. The second row represents another group of 10 trunk lines to second selectors in the **2000** section of the plant, the third row represents a group of trunks leading to second selectors in the **3000** section of the plant, etc., so that through the 10 rows of bank contacts the first selector has access to 10 second se-

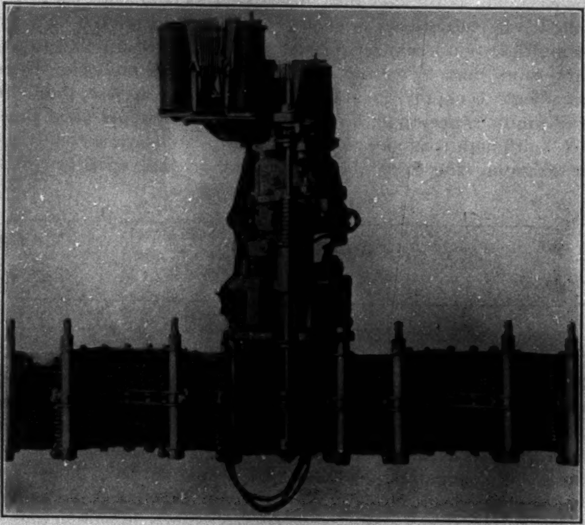


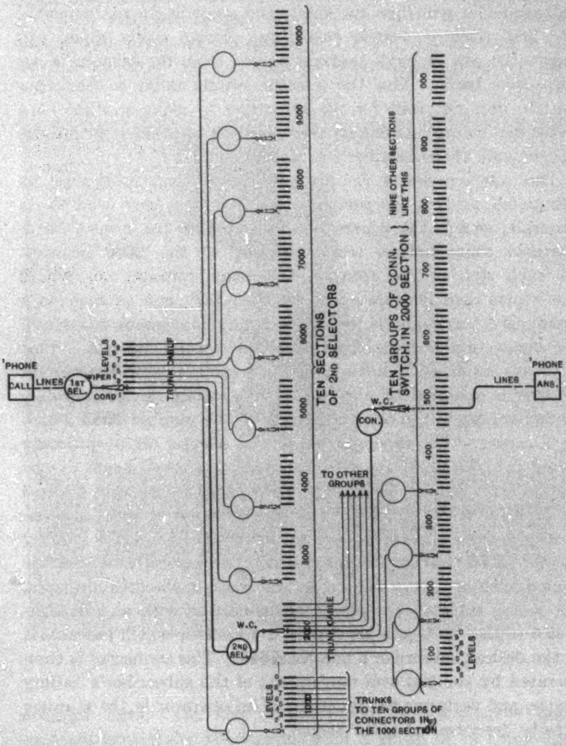
Fig. 9

lectors in each of the 10 sections of 1000 lines which make up a 10,000-line office. The first selector switch used by a calling subscriber is operated in accordance with the first digit of the number he calls. Suppose, for example, he is calling the number **2543**. The impulses sent in by the first movement of his calling device will raise the shaft, and accordingly the wipers of the first selector switch two steps, placing each wiper opposite the row of bank contacts second from the bottom in its respective bank. Now the selector switch unlike a connector switch, does not wait for the subscriber to make another turn of his dial before rotating its shaft, but the rotation is automatic and beyond the subscriber's control.

The rotation starts the instant the vertical movement is completed, and, in the particular case which is here used as an example, sweeps the wipers step-by-step over the row of bank contacts connected to trunks leading to the **2000** section. At each step of the rotation the bank contacts on which the wipers then rest are given the busy test, and as soon as a disengaged trunk line is found the rotary movement stops and the connection is completed to an idle second selector. This is all accomplished in a fraction of a second, so that the second selector is operated by the subscriber's calling device impulses corresponding to the second digit, **5**, of the number **2543** which he is calling. The wipers of the second selector are accordingly raised five steps and are then automatically rotated just as the first selector wipers were. The bank contacts of this second selector are the terminals of the trunks to the 10 sets of connectors which complete the connections to the line groups making up the **2000** section of the plant. Consequently when the second selector wipers stop on an idle trunk in the fifth multiple, the calling subscriber is placed in connection with an idle connector in the 2500 groups; that is, a connector which has access to the desired subscriber's line No. **2543**. This connector is then operated by the last two movements of the subscriber's calling device, and performs the functions of an operator in the manner already described at some length.

Fig. 10 is an endeavor to illustrate this grouping arrangement and shows the connection just described from the calling telephone to a first selector, then from the second row of first-selector bank contacts to a second selector in the **2000** section of the exchange, then from the fifth level of this second selector's bank contacts to a connector switch in the **500** group of the **2000** section, and then through the fourth row of the bank contacts of this connector to the called telephone.

It is readily understood that by thus using a first selector to pick out a trunk to any one of ten different **1000** sections, second selectors in each section to pick out trunks to any **100** group in each **1000**, and then by using the connectors to complete calls to individual lines in each **100**, that connection may be made by the use of three switches from any calling tele-



'PHONE
CALL
LINES
1ST SEL.
LEVELS
WIPER
CORD
TRUNK CABLE
0000
9000
8000
7000
6000
5000
4000
3000
2000
1000
TEN SECTIONS OF 2ND SELECTORS
W.C.
2ND SEL.
TRUNK CABLE
TO OTHER GROUPS
LEVELS
TRUNKS TO TEN GROUPS OF CONNECTORS IN THE 1000 SECTION
CON.
W.C.
TEN GROUPS OF CONN. SWITCH. IN 2000 SECTION
NINE OTHER SECTIONS LIKE THIS
000
900
800
700
600
500
400
300
200
100
LEVELS
LINES
'PHONE
ANS.

FIG. 10

phone to any number from **0000** to **9999** or in other words to **10,000** different numbers. It will also be readily understood that by using a fourth switch, called a third-selector switch, and using numbers with five digits instead of four, that the capacity of the system will be multiplied by ten and will be 100,000 lines instead of 10,000. In a system of 100,000 lines, **10,000** numbers are generally set aside for each main central office. Consequently on each call the first selector picks a trunk to the desired office, the second selector picks a trunk to the desired **1000** in that office, the third selector picks a trunk to the desired **100** and the connector completes the connection to the desired line.

Systems of 100,000 lines' capacity have been installed in a number of different cities. One of the most notable is that in Los Angeles. This system is illustrated in Fig. 11. As shown, there are six main offices, each with an ultimate capacity of 10,000 lines.

The Olive Street main office is now equipped for 10,000 lines, West for 4000 lines, Adams for 2500 lines, South for 5000 lines, Boyles for 800 lines, and East for 1000 lines. The numbers in the South Office all commence with **20,000**. Those in Olive Street Office all commence with **60,000** etc.

South office has a branch office called Vernon; West office has two branches which are called Prospect Park and Hollywood; East office has a branch called Highland Park. The numbers in each branch office commence with the same digit as the numbers in the main office to which it connects. That is; one of the sections of **1000** numbers are taken from the main office and are set aside for use in the branch. For example: the lines now equipped in South office are numbered from **21,000** to **25,000** and the numbers in its branch Vernon, run from **29,000** to **29,999**. It is, of course, unnecessary for a calling subscriber to know to which office he is connected or to which office the party he desires to call is connected.

The trunking between offices is all automatic. A subscriber, for instance, in the South office, who, on the first move of his dial turns it from the number **2**, will automatically select a local trunk line to a second-selector in South office. If he makes the first turn from the number **3**, a first selector at South office will automatically connect him to a trunk line terminating in a second selector at East office. Or, if he makes the first turn from the number **6**, the first selector at South Office will automatically select an idle trunk to Olive Street office, etc.

Suppose, a subscriber connected to the South office wishes to call **62,127**, which is an Olive Street office number. The first movement of the dial operates a first selector at South office, and extends the connection over an idle trunk to a second selector switch in the Olive Street office. The second digit **2** will operate the second selector at Olive Street office, and extend the connection to a third selector in the **2000** section of the Olive Street switchboard. The third digit **1** will extend the connection to an idle connector switch in the **100** group of the **2000** section. The last two digits will operate this connector switch and complete the connection to **27** in this particular **100**.

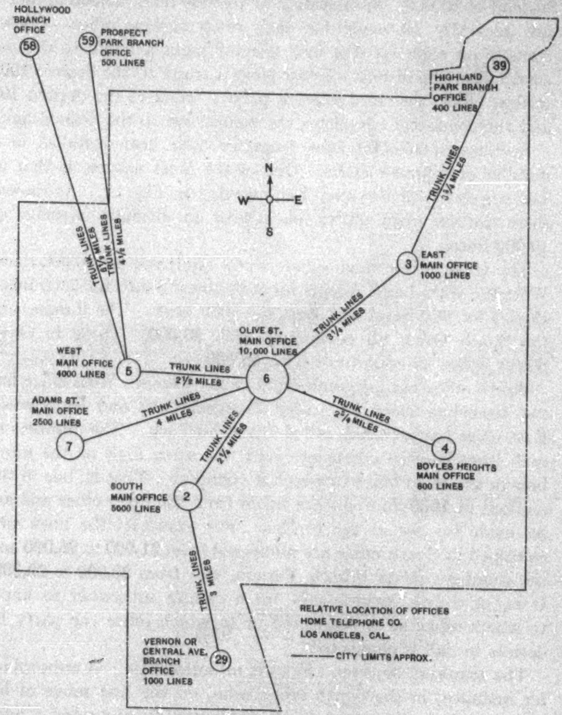

HOLLYWOOD BRANCH OFFICE
58
59
PROSPECT PARK BRANCH OFFICE 500 LINES
39
HIGHLAND PARK BRANCH OFFICE 400 LINES
TRUNK LINES 3¾ MILES
N
W
E
S
TRUNK LINES 6½ MILES
TRUNK LINES 4½ MILES
3
EAST MAIN OFFICE 1000 LINES
TRUNK LINES 3¼ MILES
OLIVE ST. MAIN OFFICE 10,000 LINES
WEST MAIN OFFICE 4000 LINES
5
TRUNK LINES 2½ MILES
6
ADAMS ST. MAIN OFFICE 2500 LINES
TRUNK LINES 4 MILES
7
TRUNK LINES 2¼ MILES
TRUNK LINES 2¾ MILES
4
BOYLES HEIGHTS MAIN OFFICE 800 LINES
SOUTH MAIN OFFICE 5000 LINES
2
TRUNK LINES 3 MILES
RELATIVE LOCATION OF OFFICES HOME TELEPHONE CO. LOS ANGELES, CAL.
CITY LIMITS APPROX.
VERNON OR CENTRAL AVE. BRANCH OFFICE 1000 LINES
29

Fig. 11

Suppose, again, that a South office subscriber is calling **39,143** which is in the Highland Park branch office. The first movement of the dial operates a first selector in the South office and selects a trunk to a second selector in the East Main office. The second movement of the dial raises the shaft of this second selector nine steps, and selects an idle trunk to a third selector in the Highland Park branch office. The third movement extends the connection through a local trunk in the Highland Park branch office, to an idle connector in the **100** group, and the last two motions of the dial result in the completion of the connection to **43** in that particular hundred.

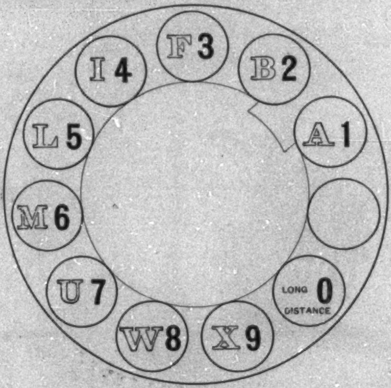


FIG. 12

It is interesting to note that the distance from Vernon office to Highland Park office is over 12 miles, and that the distances between the other offices are quite long. It is therefore apparent that the trunks between switches may be of almost any desired length. It is also to be noted that the time required to complete a connection and the number of machines used is independent of the number of offices through which a connection may be trunked.

It should be said here that in all 100,000-line systems the numbers are made up of a letter and four figures instead of five figures.

Fig. 12 shows a calling-device number disc for a system of this size. Using this arrangement **26,187**, for example, would appear in the telephone directory as B-**6187**. When operating the calling device many subscribers will remember a letter and four figures more clearly than they will five figures.

It might be inferred from the foregoing portion of this paper that there is one first-selector switch permanently connected to every subscriber's line. Formerly this was the case, but in a modern plant each line terminates in a much smaller and a cheaper device called a line switch. The line switch is not under the control of the subscriber, but connects him automatically to an idle first-selector switch the instant he removes his receiver from his switch-hook preparatory to making a call. The first-selector is, therefore, operated by the first impulses transmitted from the subscriber's calling device just as in the older systems. When the line switches are used, 10 first-selectors for each 100 lines are generally sufficient to handle the traffic.

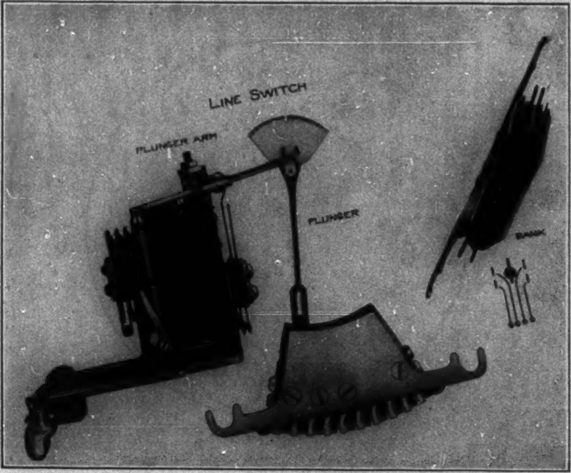


FIG. 13

Each line switch, see Fig. 13, includes the line and cut-off relays with which each line is equipped just as in manual practice. It also includes a moveable plunger arm at the end of which a plunger is so pivoted that it may be swung back and forth over the line-switch bank. The bank consists of 10 sets of springs and represents a multiple of 10 trunks to first-selector switches. The line switches are mounted in groups of 25 each on the face

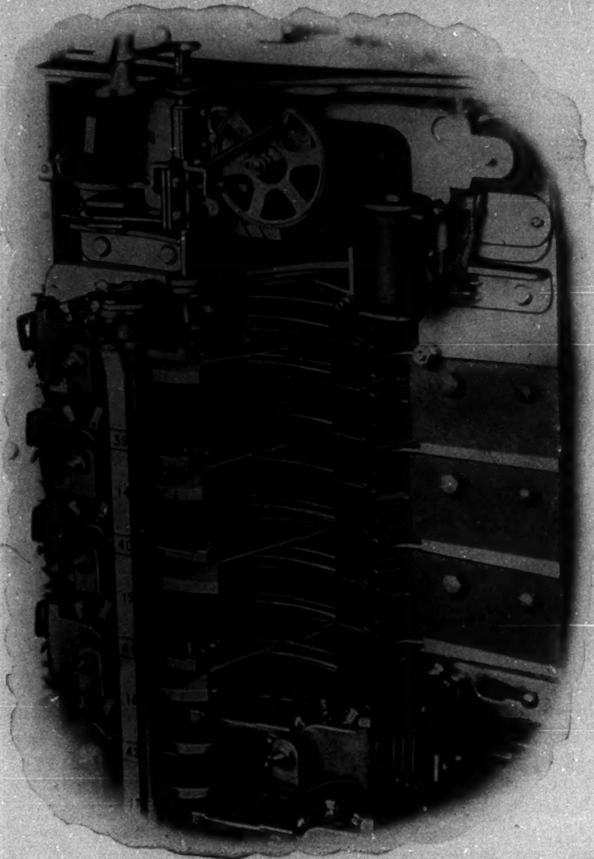


FIG. 14

of an upright in such a manner that the plungers are in alignment. See Figs. 14 and 15. The notch in the head of each plunger meshes with a rocking bar or "master shaft" as it is called. A step-by-step device called a master switch (seen in the upper part of Fig. 14) is connected to each pair or to each four master-shafts and by means of them can swing the plungers back and forth, step-by-step over the banks of contact springs. Normally the plungers are at rest poised over bank contacts multipled to an idle trunk.

When a subscriber removes his receiver from his telephone switch-hook preparatory to making a call, a circuit is thereby closed which causes the plunger arm of his line switch to be instantly pulled down, carrying its plunger out of engagement with the master-shaft and thrusting it into the bank. The effect of this is to connect the subscriber's line to a trunk leading to an idle first-selector switch, as shown diagrammatically in the right-hand portion of Fig. 15.

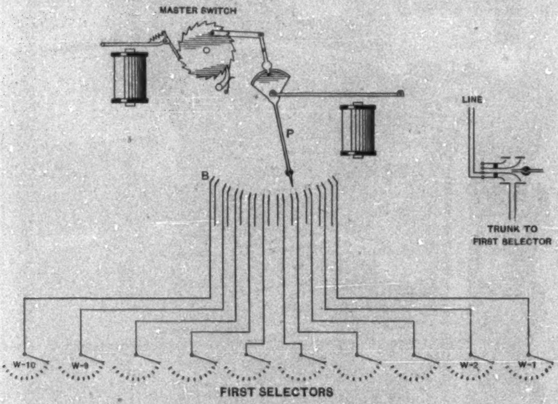


Fig. 15

The instant that one line switch thrusts its plunger into the bank, thus occupying the trunk over whose multiple all idle plungers have been poised, the master-switch operates and swings the remaining idle plungers forward over the next multiple of bank contacts. If this trunk should be busy, the movement pro-

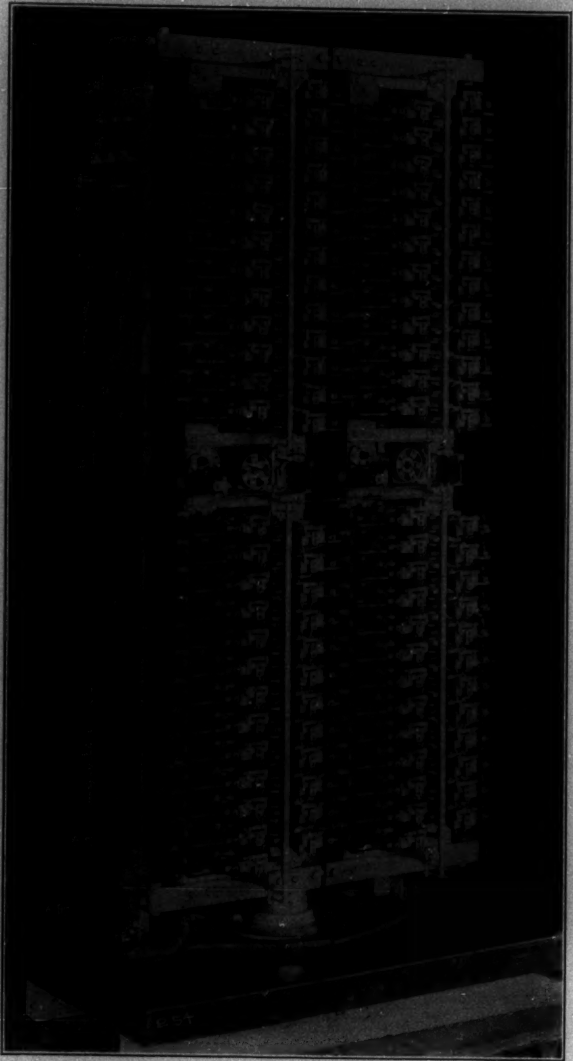


Fig 16

ceeds until an idle trunk is found. It is to be noted that a line switch always uses a pre-selected idle trunk instead of making a selection after a subscriber starts to call as the Strowger selector switches do. This is quite an important feature and saves considerable time in establishing a connection.

Ordinarily the banks of 100 line switches are multipled together and connected to 10 first-selector trunks, but for four-party line service or extra heavy traffic, the number in one multiple is often reduced to fifty. Fig. 16 shows a front view of a complete line-switch unit with 100 line switches and two master-switches mounted. Only one master-switch is used at a time, the other being held in reserve. Fig. 17 is a rear view of the same unit showing how the 10 connector switches used for handling calls incoming to any 100 lines are mounted on the same upright as the line switches handling their outgoing calls.

While the primary object of the line switches was to reduce the cost of the switchboard by eliminating 90 per cent of the comparatively expensive first-selector switches, they have also simplified the central office equipment and have reduced the space required for it. Further, they have resulted in several new and somewhat radical departures in the art of building automatic telephone systems. The most important of these is the line-switch district station which enables very considerable savings to be made in underground and aerial cable.

A district station is installed by placing one or more line-switch units complete with connector switches in a small building at the telephonic center of a district, generally a mile or more distant from the nearest central office. The lines of all telephones in the district are brought to the district station and are there connected to the line switches. The first selectors to which these line switches are trunked remain at the nearest large central office, consequently when a district station subscriber removes his receiver from his switch-hook preparatory to making a call, his line switch instantly puts him into connection by means of a trunk with a first-selector switch at central office. The connector switches for handling the calls to the district station telephones are mounted in their usual places on the back of the line-switch units, and are connected by trunks to the banks of second selectors, also located at the nearest central office. Thus all calls from and to the district are handled over trunks instead of over subscribers' lines.

Since, as already stated, there are usually but 10 first

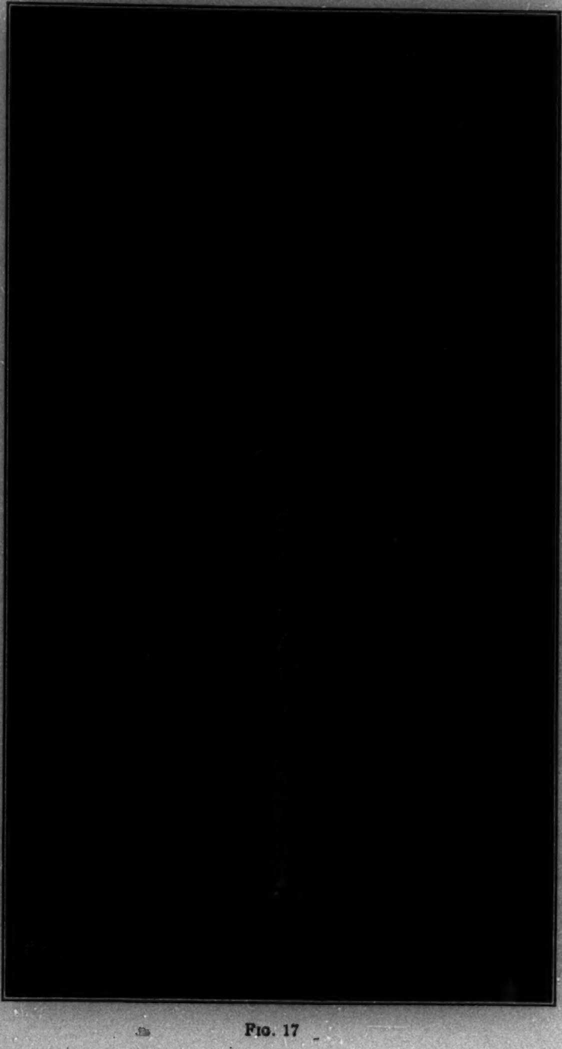


FIG. 17

selectors and 10 connectors for each 100 lines, and since but three pairs are needed for testing and supervisory circuits to the district station, a total of 23 trunk pairs is sufficient between the station and the central office. This leaves a net saving of 77 pairs of wires per 100 lines. In district-station practice stations of less than 500 subscribers are generally unattended and supervised entirely from the central office to which they connect. This is so thoroughly worked out that the wire-chief can test every line entering each district station without leaving his desk at central. Stations of 500 lines or more are generally put into a combination residence and office building so that one attendant living in the building gives the equipment all the attention that it may require at any time.

FIG. 18

Fig. 18 shows the exterior of a typical line-switch district station building 15 ft. by 16 ft. with a capacity of 700 lines. Fig. 19 shows the interior of one equipped for 200 lines.

Fig. 20 is a sketch of a notable system in Columbus, Ohio, using one large central office of approximately 10,000 lines, surrounded by 9 district stations, varying in size from 100 to 600 lines. One of these 100-line units in Columbus was installed as an experiment in an underground vault about the size of an ordinary underground manhole, and has now been so operating for about two years.

One can readily imagine that the trunking scheme of this system would be very complicated if each of the small offices shown in the illustration had trunks to each of the other offices. Furthermore the cost of trunks divided into such small groups would be so much greater, that the saving in line wires would be much reduced and in some instances almost wiped out. But using the district stations each having trunks to no office except the central office (placed near the business center of the city) the trunking plan is a very simple and economical one, and the conditions for centralized supervision of the system are practically ideal.

FIG. 19

A new feature called a secondary line-switch has very recently been introduced into the automatic system. The mechanical construction of this switch and of its bank is the same as that of the regular or primary line-switch, and it is mounted and controlled by a master-switch in the same manner. The purpose of the switch is to reduce still further the required number of first-selector switches, and their trunks. As explained, it has been the general practice to install a number of first selectors equal to 10 per cent of the number of subscribers' lines. Observations made in numerous plants at the busiest hour of the day, however, show that at the peak of the load not more than from 1.5 to 5 per cent of the subscribers are using first selectors. The percentage is smaller in the larger plants and greater in the smaller plants, being about 5 per cent for a plant of 1000 lines and not over 2 per cent for a plant of 10,000 lines. This reduction in the percentage of trunks required as the number of subscribers' lines increases, follows a law well known among telephone engineers. The secondary line-switch takes advantage

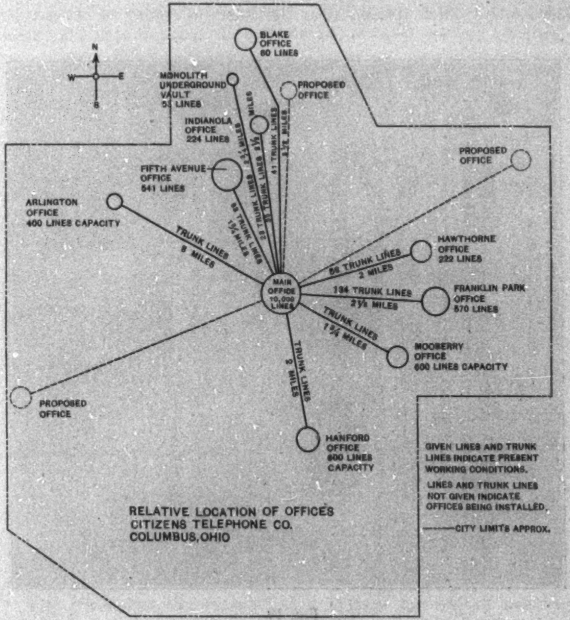

N
W
E
S
BLAKE OFFICE 60 LINES
MONOLITH UNDERGROUND VAULT 53 LINES
PROPOSED OFFICE
INDIANOLA OFFICE 224 LINES
FIFTH AVENUE OFFICE 541 LINES
ARLINGTON OFFICE 400 LINES CAPACITY
TRUNK LINES 8 MILES
98 TRUNK LINES 1¾ MILES
23 TRUNK LINES
22 TRUNK LINES
41 TRUNK LINES
MILES
MAIN OFFICE 10,000 LINES
PROPOSED OFFICE
HAWTHORNE OFFICE 222 LINES
56 TRUNK LINES 2 MILES
134 TRUNK LINES 2½ MILES
FRANKLIN PARK OFFICE 570 LINES
TRUNK LINES 1¾ MILES
MOOBERRY OFFICE 600 LINES CAPACITY
TRUNK LINES 2 MILES
PROPOSED OFFICE
HANFORD OFFICE 600 LINES CAPACITY
GIVEN LINES AND TRUNK LINES INDICATE PRESENT WORKING CONDITIONS.
LINES AND TRUNK LINES NOT GIVEN INDICATE OFFICES BEING INSTALLED.
CITY LIMITS APPROX.
RELATIVE LOCATION OF OFFICES
CITIZENS TELEPHONE CO.
COLUMBUS, OHIO

FIG. 20

of this principle by making it practicable to give 2000 or 2500 subscribers' lines access to one group of 100 first selectors. The secondary switches are inserted between the line-switches and the first selectors in such a way that the primary line-switches pre-select idle secondaries and the secondaries pre-select idle first selectors. Therefore, when a subscriber lifts his receiver from the switch-hook preparatory to making a call, his line-switch and the secondary to which it connects him operate almost in unison. This re-selection of trunks, combined with a rather complex system of cross-multipling, accomplishes the desired result of giving a large number of subscribers access to one group of trunks, and thereby reduces the number of trunks and first selectors. It is obvious that if the first selectors are at a considerable distance from the line-switches, for example, in a central office while the primary and secondary line-switches are in a district station, that these secondary switches will save materially in the cost of trunks to the first selectors.

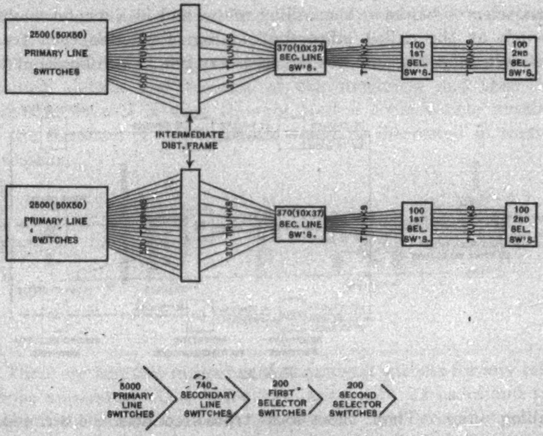

2500 (50X50) PRIMARY LINE SWITCHES
500 TRUNKS
370 TRUNKS
370 (10X37) SEC. LINE SW'S.
TRUNKS
100 1ST SEL. SW'S.
TRUNKS
100 2ND SEL. SW'S.
INTERMEDIATE DIST. FRAME
2500 (50X50) PRIMARY LINE SWITCHES
500 TRUNKS
370 TRUNKS
370 (10X37) SEC. LINE SW'S.
TRUNKS
100 1ST SEL. SW'S.
TRUNKS
100 2ND SEL. SW'S.
5000 PRIMARY LINE SWITCHES
740 SECONDARY LINE SWITCHES
200 FIRST SELECTOR SWITCHES
200 SECOND SELECTOR SWITCHES

Fig. 21

Fig. 21 shows the use of secondary line-switches in the general trunking equipment scheme for one of the automatic offices now being installed in Havana, Cuba. This office is equipped for 5000 lines. The line-switches are divided into two large groups each of 2500 lines, and each consisting of 50 small groups or multiples of 50 lines each. The trunks from a 2500-line group pass through an intermediate distributing frame to 370 secondary line-switches, arranged in 10 sets of 37 each. Each of the 10 sets has trunks to 10 first-selector switches. Thus, all calls from 2500 lines will be handled by 100 first selectors.

An automatic system equipped for 15,000 lines divided among four offices, was installed in San Francisco last year. Secondary line-switches are there used between the line-switches and the first selectors and are also used to reduce the trunks between offices. In former practice each inter-office trunk terminated in first-selector banks at the calling office, and in a second-selector switch at the called office, but in San Francisco each trunk between offices terminates in secondary line-switch banks at the calling office. Then, short local trunks connect the secondary line-switches to the first-selector banks. Fig. 22, illustrates the trunks outgoing from Main office to Howard, West, and South offices, indicating that the secondary line-switches reduce the trunks to Howard office from 120 to 60, the trunks to West office from 70 to 35, and the trunks to South office from 70 to 35, by combining the trunks coming from the first-selector banks in groups of 10 each, into one group to each office.

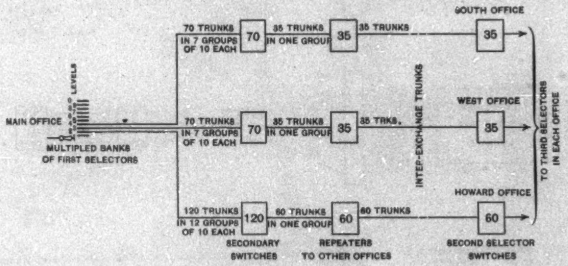

SOUTH OFFICE
70 TRUNKS
IN 7 GROUPS OF 10 EACH
70
35 TRUNKS
IN ONE GROUP
35
35 TRUNKS
35
LEVELS
0
9
8
7
6
5
4
3
2
1
MAIN OFFICE
MULTIPLED BANKS OF FIRST SELECTORS
70 TRUNKS
IN 7 GROUPS OF 10 EACH
70
35 TRUNKS
IN ONE GROUP
35
35 TRKS.
INTER-EXCHANGE TRUNKS
WEST OFFICE
35
TO THIRD SELECTORS IN EACH OFFICE
HOWARD OFFICE
120 TRUNKS
IN 12 GROUPS OF 10 EACH
120
60 TRUNKS
IN ONE GROUP
60
60 TRUNKS
60
SECONDARY SWITCHES
REPEATERS TO OTHER OFFICES
SECOND SELECTOR SWITCHES

Fig. 22

Inter-office trunks in automatic systems are equipped with another piece of apparatus which is also indicated in this sketch and which is called a repeater. This is simply a set of relays, and derives its name from the fact that it repeats the calling-device impulses from the subscriber's line to the trunk. It serves another important purpose, for through its relay coils, talking current is supplied to the transmitter of the calling subscriber.

Talking current is always supplied to the called subscriber's telephone through the connector switch used in calling him. Such an inter-office talking circuit is shown diagrammatically in Fig. 23. Each subscriber always receives talking current from the office in which his line terminates. This is in conformity with the best practice which requires that the subscriber's "loops" shall be as short as possible, and as nearly alike in resistance as conditions will allow. This makes it practicable to supply all transmitters with sufficient current through small and economical line wires, and to supply them all with comparatively the same amount of current.

The length of this paper precludes a discussion of the mechanical details and circuits of the machines and their accessories, even if it were thought that a considerable number of the members of the Institute would be interested in such a discussion.

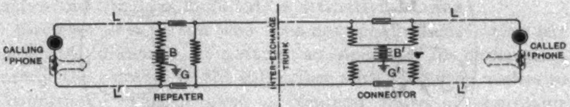


FIG. 23

There are just two measures of permanent success for any telephone apparatus. One is its popularity with its users and the other is the profits it affords the owners. Numerous investigations, some of them made on a very large scale have, to the best of the writer's knowledge, always resulted in the verdict that automatic telephone service is preferred to manual service by the large majority of telephone users, and while the first cost of the equipment is greater than that of manual equipment, the elimination of operators' wages, the saving in building space, and the savings in cable and conduit (discussed at length in the writer's Atlantic City convention paper) have generally made automatic equipment a more profitable investment than manual equipment.

While a considerable number of small private automatic plants are in use, public automatic systems are generally confined to cities and the larger towns. For where a manual switchboard is so small that during a considerable portion of the day one operator can make all local connections and, in addition, handle all rural and long-distance calls, it is very difficult and generally impossible for an automatic switchboard to compete with it. The larger the system the more economical automatic apparatus becomes. It is a matter of common engineering knowledge that automatic machinery is not warranted in any class of work until the output desired becomes sufficiently large.

STATING THE CASE DIFFERENTLY

When automatic machinery is substituted for manual labor it is generally for three purposes.

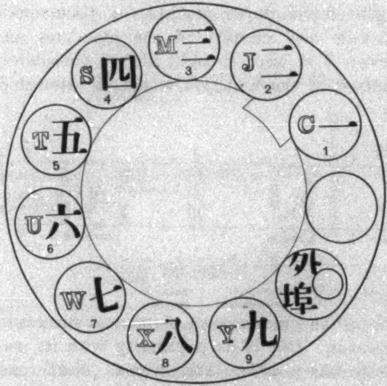


FIG. 24

1. To increase and quicken production.
2. To reduce the cost of the product.
3. To secure uniformity both in the quality or form of the product and in the time required to make it.

These results have been generally attained by automatic machine telephone switchboards.

Among the reasons for the popularity of the service it may be noted that almost every one likes to feel that the making and breaking of each connection is entirely in his own control. The quickness with which connections are obtained appeals to the subscribers, and in relation to this it may be said that while connections are generally obtained more quickly than in manual service, the difference in time seems much greater to the subscriber than it really is, for two reasons: first, he is occupied in turning his dial while the connection is being put up, and the time, therefore, passes more quickly than it would were he waiting for an operator. Secondly, subscribers generally answer calls received through automatic telephones more quickly than those received through manual telephones. This can readily be explained by an example: For instance, a grocer will answer his automatic telephone more promptly, because he knows that the customer calling him will hold him directly responsible for any delay; otherwise the switchboard operator would probably get the blame.

The instantaneous disconnection is another good feature which is appreciated by any one who has occasion to call several numbers in rapid succession.

Bankers, doctors, and others, who have private matters to discuss over the telephone wire appreciate the comparative secrecy of the system.

The uniformity of the service at all hours of the day or night, holidays and Sundays included, is attractive to many.

A foreigner or a person who does not speak plainly often has considerable difficulty in getting an operator to understand correctly the number of the subscriber with whom he wishes to be connected. This is even a common cause of complaint among telephone users who move from the southern part of our own country to the northern part. Fig. 24 shows a calling-device number disc such as used in the Chinese quarter of San Francisco. This disc is equipped with Chinese characters, and up to this time the section of the automatic switchboard which serves "Chinatown" is one of the busiest in the exchange.

A WORD WITH REFERENCE TO THE FUTURE

Although inventors have been giving attention to automatic switchboards as long as to manual switchboards, and although automatic equipment has passed through as many stages of development, and in many instances through stages of development similar to those through which the manual apparatus has passed, yet the former has not by any means reached the dead level of "no more beyond" that the latter has. From one view point this is discouraging, but on the whole it is inspiring, for while those who are most familiar with automatic equipment are most painfully aware that it has not yet been brought to its highest possible state of development, they are, at the same time, its most enthusiastic admirers, and they hope, by further development, simplification, and reductions in first cost, that many families who cannot now afford telephone service of any kind will have it offered to them at a price which they can pay and that the telephone will thus eventually become a universal household necessity. They also hope that the automatic operation of many long-distance lines will greatly increase their capacity and consequent efficiency. This has been tried on a small scale between Columbus and Dayton, Ohio, with very encouraging results. Inasmuch as both of these cities are equipped with automatic switchboards for local service, it was only necessary to have a toll line terminate in the automatic switchboard in one city and in a calling device before a long-distance operator in the other city to make a trial. It was found that connections could be put up much quicker than in the ordinary way. This plan is used very satisfactorily by several automatic companies for handling their own short local toll lines, by giving the operator at each suburban town a calling-device, and allowing her to call all parties in the city automatically without any supervision at the city end of the line. While the opportunity for an operator cheating the company by not reporting all fees earned and collected is greater than with double checking, this has not been found to be a serious drawback. In fact, it is possible to bridge an ordinary stock ticker across the line in such a way that it records every call the operator makes and the length of every conversation. It has been found, however, that the knowledge that this could be done, and might be secretly done at any time, has been sufficient to prevent any tendency toward dishonesty. Careful tests and comparisons made by one company using a considerable number of these short automatic toll lines showed that sufficiently busy lines handled three times the number of conversations that was possible with the former arrangement.

DISCUSSION ON "MODERN AUTOMATIC TELEPHONE APPARATUS," NEW YORK, FEBRUARY 11, 1910

Chairman Maver: It may be of interest to note that in telegraphy two general systems are employed, namely, manual telegraphy, and automatic telegraphy. The first relates to the hand transmission of messages and the second to the machine transmission of messages. In telephony we also have manual and automatic systems, so called, but these relate to the manner in which subscribers' circuits are coupled into one metallic circuit at the exchange and have nothing to do with the transmission per se of communications, which is of course effected by the subscribers' voice. It is of course well known that in the present day practice of telephony each subscriber in a given district is connected with central by two wires, the terminals of which, in the manual system, are led into a switch board in the exchange and normally end there. There is in the circuit of these wires a relay which closes a circuit containing a small incandescent lamp which lights up when the subscriber lifts his telephone receiver from the hook, thereby indicating to the attendant operator in the exchange that a connection is desired. Upon listening in and ascertaining the number of the desired subscriber the operator by means of jacks and cords performs the operation of placing the lines of these subscribers in a through metallic circuit, ready for intercommunication. In a large exchange one operator can attend to the calls of about two hundred subscribers. In automatic telephony on the other hand the operation of coupling up the circuit of a calling subscriber with any other subscriber is performed automatically in the exchange by selecting and connecting apparatus controlled by impulses of electric current established primarily by the calling subscriber.

The question of automatic telephony is perhaps not a very active issue with us in the East at present, but it is decidedly so in the western part of this country, where it is in quite extensive operation, and also to a smaller extent in the eastern part. For instance, New Bedford and Fall River, Massachusetts have automatic telephone exchanges that have been in successful operation for the past eight or ten years.

I am sure, that we all feel under obligations to Mr. Campbell and to the company with which he is associated, for their courtesy, in not only presenting the paper, but also in bringing before us this model working exhibit of the apparatus, and on behalf of the Telegraphy and Telephony Committee, I desire to express our hearty appreciation of this courtesy.

Before calling for discussion, I will ask Mr. Campbell to kindly show us the manner in which the ringer arrangement acts in this apparatus and also to point out the location of the Keith line switch.

(Mr. Campbell then briefly described the apparatus and gave further demonstrations.)

Ralph W. Pope: A discussion of a system of this kind naturally brings up a comparison with other systems. We have been through various discussions of that kind in this room, that have sometimes raised the temperature appreciably. This is a case, however, where we are not called upon to discuss the question of whether or not the apparatus works, because we know that it does work. I think that our vision can be cleared sometimes by taking a reverse view of the conditions. There is always some doubt as to whether an automobile is better than a horse, but if we always had had automobiles, would we use horses to supersede them? So, if we had always had the automatic telephone system in use, would we be talking about introducing the manual system as an improvement.

I have been much gratified, in reading over the paper, to see the modest claims made by the author, and to note that he has refrained from saying that the automatic system will answer in every place and under all conditions. In a certain sense, I am quite familiar with it, so far as lapse of time is concerned. I was Chairman of the Committee on Telegraphy and Signalling at the World's Fair in Chicago in 1893, when we examined the Strowger system which was at that time on exhibition. I believe that it did not receive an award, because of its crude construction, and it was felt that it did not appear equal to the claims made for it; and I think I am safe in saying that it was not then in use to any great extent. Rather curiously, we considered at that time the question whether it was really adapted to large cities, and it seemed to be the opinion that it was better adapted for the smaller cities and the question of its suitability for the larger cities had not been proved. Since 1893 its utility has been proved, and here in New York, where we are supposed to be able to get the best of everything there is, and to see everything that is worth seeing, it remained for the American Institute of Electrical Engineers to have a working exhibit of this automatic telephone system for the public to come and examine.

Last summer I visited the Pacific coast, and there, for the first time since my experience in Chicago some seventeen years ago, I had the opportunity of examining the automatic system in operation in Portland, Oregon. It was rather a novel experience to be in that exchange of about eight thousand lines, and to see the connections, or rather hear them, being made throughout the room, with practically no one in attendance at all; and another thing I learned there in Portland, from our own members, who were simply subscribers to the automatic system, was that from their experience they preferred the automatic system to the manual system, on account of its certainty of conveying the signals, and not giving the wrong numbers. Another point, which was new to me, and which was first made known to me by a subscriber who was an electrical man and had an automatic exchange system connected with his residence, was that occasionally a lineman came looking for trouble on the circuit before the subscriber knew that there was any trouble. It appears that in the exchange, instead of waiting for trouble to be reported from the outside, they can locate the trouble on the line from the exchange and remove it promptly before the subscriber is aware that there is any trouble.

Another interesting device connected with the system, which was called to my attention, was the meter for registering the calls. It appears that in some of the cities on the coast the franchise requires that the telephone exchange system must be on a meter basis, that is, that the subscriber must pay by the number of calls. The result is that the companies are obliged to meter the system, and the meter not only registers completed calls, but it discards " service " calls and discards calls that are not completed, so that the meter actually registers only the calls that are to be paid for.

From Portland, Oregon, I went to San Francisco, and there the Home Telephone Company's system was in process of construction. I visited the main exchange and several of the branches, and it is quite certain and evident that the people who are building that system have faith in the automatic telephone exchange, for the reason that it is one of the best and most expensively constructed systems that I have ever visited—all the exchanges are fire-proof, the wires are underground, led up in lead-covered cables, and as far as I could see no expense has been spared to make the installation first-class in every particular.

It must be remembered that the manual system may be properly divided into two classes, so far as the subscriber is concerned—the subscriber may work direct with the exchange or he may work through a private branch exchange. In the course of my experience I have found that the perfection of the manual system depends very largely on the disposition, the voice and the attention of the particular operator that has charge of the section with which one is connected. I feel that with the introduction of a private branch, while the operator usually has less on her mind, that we do not receive the short and petulant answers, and the impression that we are trespassing on the time of somebody, and we had better be quick about it, that we get when we are connected with the main exchange. Right here, while this has no bearing particularly on the paper, I think it is well for all of us to remember, and I presume we have criticised it—that when the operator at the exchange repeats back the number wanted, we can rarely understand what the number is, and if you wish to correct it, the operator has gone, so that that time is practically lost, and I understand that the practice has been abandoned in some of the exchanges for that reason. It may have been due to Mr. Campbell's Chicago voice that he brought with him to-day, but when he undertook to make a telephone connection from my office, he succeeded twice in getting the wrong number, and we began to think that the number was wrong in the book, but I believe he finally succeeded in getting connection with the subscriber. I am free to confess that this was a rather bad exhibit to make of the manual system to a gentleman who came here with this exhibit we see to-night.

Chairman Maver: I will make some additional remarks, and read one or two communicated discussions, to one of which Mr. Pope has referred. As Mr. Pope has said, Mr. Campbell is quite modest in his claims, and therefore, even if one were disposed to be critical, not much opportunity is afforded. Mr. Campbell presents his apparatus almost as though it were on trial, whereas it is in actual operation on a large scale in over fifty cities and towns in this country, embracing a total of 250,000 subscribers.

Mr. Campbell refers to the somewhat crude apparatus first employed in the system which he has described in his paper, in which the calling subscriber pushed buttons corresponding to the call number of the called subscriber. There were, however, more cumbersome ways than this employed in some of the early automatic telephone systems, to one of which (the Callendar automatic telephone) I may refer, as it may help to show the manner in which our predecessors sometimes groped about to reach a desired point; just as our successors will no doubt observe that we of 1910 have only been groping in many things, where we imagine we have reached the acme of perfection. The Callendar automatic telephone was, I believe, in limited use for some time in this country. By reason of its awful and wonderful design it is worthy of passing mention. Each subscriber's wire was led into the central exchange in such a manner and so arranged with regard to certain mechanism that when a subscriber called he was first connected with a "numerical receiver." This numerical receiver had a movable grooved arm, in the form of a rail, which was adapted to make contact with certain other rails as required. In a suitable receptacle were kept a number of metallic balls, which were allowed at the proper moment to roll into the traveling rail from which they were delivered to the subscriber's rail. The subscribers' rails were placed across certain conductors normally not touching. At each point on a rail, where it crossed a conductor, a trap was placed in the rail. When any one of these traps was opened a metallic ball coming down the rail fell through the trap and made contact with the conductor below. Each subscriber was allotted a rail and a cross conductor. When, then, a certain subscriber desired a certain other subscriber, he would give the necessary impulses of current which would bring the traveling rails into position with the rails of the desired subscriber, and the metallic ball would then pass from this receptacle on to the subscribers rail up to the point where a trap was found open, when the ball fell through and made connection with the subscriber's cross-connected conductor. In short, by the mechanism employed in this system, the subscribers, by a process of selection, were finally automatically connected and they were isolated from other subscribers while thus connected. When through, one or other of the subscribers pressed a release button; the traps were closed and the balls were returned automatically to their receptacle, ready for other calls.

It is to be feared that if automatic telephony depended on a system involving contact by movable rails and rolling balls it would be within bounds to predict that hopes of its ever attaining commercial usefulness would be meagre.

One of the most frequent objections that was offered to automatic telephony in its early days was that the multiplicity of contacts necessarily employed would prevent its successful operation, and it used to be pointed out that whereas in a manual exchange for 5,000 subscribers there are, for instance, something like 133,000 pairs of contacts, in an automatic exchange for 5000 subscribers there might be 1,000,000 pairs of contact in the first selectors alone. The introduction of the Keith line switch, however, has reduced the number of such contacts in the automatic exchange by perhaps eighty per cent. Even, however, before the introduction of the Keith switch, comparatively little trouble was experienced by the great multiplicity of contacts in the automatic exchange; and from actual observation it is my experience that such troubles are quickly indicated by supervisory signals.

Another point that may be mentioned is that the wear and tear on the automatic apparatus is inconsiderable. This is partly due to the fact that much of the apparatus is not in operation more than 2 to 5 per cent of the time. Apart from this fact, actual experiments with certain automatic apparatus, where the mechanism was operated by machinery over 1,000,000 times, shows that the wear of the parts was not perceptible.

There is no doubt that the large amount of apparatus and the multiplicity of contacts employed in the automatic coupling of subscribers circuits tends to the occurrence of troubles that are unknown in the manual systems. An instance of these troubles of comparatively frequent occurrence is the "off normal" troubles, due to a failure of some part of the apparatus to complete its full function or to return to normal position. This for example may be due to sticking of the wipers in the bank contacts, to imperfect contacts, etc. In the common battery system of the manually operated exchange there are numerous delicately adjusted relays operated automatically, and in the multiple switchboard of the same system there are countless contacts, jacks and cords, subject to handling in no delicate manner, and all conducing more or less to the production of defects, but it may fairly be assumed that the occurrence of contact and apparatus troubles in the manual system is less frequent than in the automatic system.

It is, however, a fact that while the occurrence of such troubles is comparatively frequent in the automatic system, nevertheless the methods adopted to promptly announce or indicate the occurrence of defective operation to the attendants, by supervisory lamps and other signals, are so efficient that in the large majority of cases the defects are discovered and rectified before the subscribers concerned are aware that such troubles have existed. Further, the attendants become so accustomed to the rhythmic sounds of the apparatus in the process of making normal connections that their ear detects any abnormal operation of a piece of apparatus almost before the supervisory signal can indicate the defect. By reason of this ability of the attendants to recognize non-completed calls they are frequently able to assist in completing a call. This is done by cutting in on the calling subscriber's line to inquire the number of the called subscriber, on learning which the attendant rotates the various parts of the apparatus manually as required for the proper connection. I believe that a daily average of about 16 such " assist " calls has been noted in one large automatic exchange. In consequence also of this ability of the attendants to forestall and to quickly rectify apparatus troubles in the exchange, the disadvantage of the occurrence of such troubles loses much of the weight it might otherwise possess. Obviously, in this as in many other systems, electrical and mechanical, constant vigilance is the price of good service.

The advantages rightly claimed for automatic telephony are numerous. Of course the most important one is that of dispensing with the need of operators at the exchange, not only in effecting a large saving in operating expenses, but also by solving the " girl " problems in the exchanges, which involve training the girls, their leaving the service abruptly when trained, the necessity for resting rooms in the exchanges, etc. These problems, together with the difficulty in obtaining operators suitable for the work in certain localities, have frequently been the deciding factors in determining the adoption of an automatic exchange. There is also the further important advantage that, in the aggregate, much time is saved in the automatic method of connecting, and more especially of disconnecting, subscribers, which admits, among other things of the use of a lower percentage basis of apparatus and of trunking circuits.

It is also evident that the percentage of " wrong number " calls is, in the nature of things, much higher in manual than in automatic exchanges, the difficulty in hearing numerals by telephone, and the repetition from voice to voice accounting for much of this confusion. There is perhaps no greater single cause of annoyance to subscribers, and of loss of valuable time in effecting connections to a telephone company, than this matter of " wrong number " calls. The claim for secrecy in the automatic system does not have much weight with me although it appears to do so with the general public. It is my experience that the operator in a busy manual exchange has little time and less inclination to listen to the subscribers conversation.

As the result of a wide investigation of automatic telephony in the United States and Canada, I can confirm the claims made for automatic telephony by its advocates as to its popularity with the general public where it is established, especially that basic feature of the art which enables the subscriber to make his own calls without the intervention of an operator.

E. A. Mellinger: A field for further development of the automatic system is suggested by Mr. Campbell's reference to small exchanges. Since a very large proportion of the telephones in use in the country are in exchanges of 500 lines or less, the development of a simple inexpensive switchboard designed especially for use in the small town exchange would go far toward making the telephone universal.

Aside from the economic consideration pointed out by Mr. Campbell, the chief problems which present themselves as affecting the practical operation of small automatic exchanges using the present type of equipment are the maintenance of the battery supply and the care of the apparatus. These problems are successfully solved in the case of private installations, as is indicated by the number of these exchanges in use in government and state institutions, industrial plants, mines etc.; but in these instances ample facilities exist for charging storage batteries and a competent electrician is usually at hand to attend to trouble which might arise, or to make needed adjustments or changes. The average town exchange of one hundred lines or thereabouts is at a serious disadvantage with respect to these items, which it would appear might be at least partially overcome by the use of simple equipment constructed especially for this kind of service.

Concerning the economic disadvantages of small automatic exchanges, it would be of interest to some to know how large an exchange must be to justify the use of automatic equipment as now installed, and what factors are to be considered in making a comparison. A consideration of the data available from a number of both manual and automatic exchanges indicates that the automatic begins to show an economy at about 500 lines. In a typical modern manual plant of this size there are employed eight operators at an annual expense of $2,160. As against this, an automatic plant of 500 lines has one operator or clerk and a switchman, totaling $1,100.00 per annum, thus showing a net average in operation over the manual exchange of $1,060.00.

Assuming that the automatic equipment, telephone and switchboards, will cost $8,500.00 in excess of the manual equipment, and allowing on this excess investment six per cent interest and six per cent for depreciation, we find that these annual charges amounting to $1,020.00 are just about equivalent to the saving effected in maintenance and operation. The other factors entering into consideration total about the same in each case, and would not appreciably affect the result, except that the smaller floor space required for the automatic switchboard would be an item in its favor.

Local conditions in small exchanges vary so greatly that this figure of 500 lines cannot, of course, be taken as authoritative. Public automatic exchanges of fewer than 200 lines have been operated satisfactorily and economically, but it is probable that under present conditions the average exchange of less than four or five hundred lines cannot afford to install automatic equipment except that the greater popularity of automatic service might be considered as an economic advantage as it undoubtedly is in most instances where competition exists.

E. L. Lehman: Mr. Campbell's description of the working of the automatic telephone appears to be well set forth, but what about the apparatus that does not work or cannot report when out of order? After all, it is the efficiency of repairs and cost of maintenance that satisfies the subscriber and lowers the rental charge. The fundamental requirements of operation to be met in maintaining both the manual and the automatic systems may be briefly summed up as follows: The "busy" and "trouble back" signals, "don't answer," "receivers off," and line and trunk troubles. In the manual switchboard any trouble occurring with the "busy" or "trouble back" signals would be noticed instantly a connection was put up. "Don't answer" reports are given to the calling subscriber if the called subscriber does not answer. In the case of a business subscriber or the calling subscriber insisting that the called subscriber is within hearing of his telephone a report of "can't raise" is given to the wire chief who makes a test on the line and quite often finds the line in trouble, in which case repairs may be quickly made.

Another important item in maintaining telephones is the loss of incoming calls to subscribers who have left their receivers off the hook. In a manual exchange of about 6,000 stations, a percentage of about 1.5 per day is comparatively small, and the percentage to total calls outgoing and incoming would amount to one-quarter of one per cent. Yet if these stations had their receivers off all day the loss in outgoing and incoming calls would amount to the considerable sum of 1,200, or three per cent of the total calls for the day. It is safe to say that, with the present system of plugging out on the manual system, very few calls are lost, as the subscriber is reminded to hang up his receiver by a high frequency tone thrown on the line.

Relative to lines in trouble; operators are quick to report swinging grounds, receiver circuits open due to tips out, etc., poor transmission, etc., while the plugging-out system takes care of a large percentage of instrument, line, cable and office trouble, such as shunts, grounds and open circuits. Trouble on trunk lines, office to office, may be intermittent yet are quickly noticed by an operator.

One more comparison occurs to me, namely, the calling of private branch exchange numbers or any subscriber that has two or more lines, generally numbered in consecutive order. In the manual operation, if such a subscriber is called, and the number called is busy, the connection will be put upon the next available trunk line, while the automatic subscriber would probably have to look up the number and call until a trunk line not busy was found.

Query: Can the automatic system be controlled to such an extent that a subscriber's station may not be out of order over a period of two or three hours before the fact is known by the switchman?

H. W. Pope: Some fourteen years ago I met Mr. Campbell at Augusta, Georgia. One of the first systems of automatic telephony was introduced in that city, with one selector, as I recall it, to each line. It was a very crude affair, and the wonder to me was that it worked at all, and I presume it was very largely due to the care of the man in charge of it that it did work.

There are some things that this paper hardly touches upon—in fact, you would hardly expect it to—and these are the questions of maintenance and of depreciation. Now, I have an idea that the cost of maintenance is a very large item in connection with the automatic system. I am laboring under the impression that it requires a skilled man for every thousand telephones, which would be quite an item in a large exchange, for skilled men do not work for nothing, and this system is particularly applicable to large exchanges. Of the matter of depreciation, I have no reliable knowledge. I understand there has been a system in operation in Fall River for something like ten years, which has shown a depreciation not to exceed, I think that of the manual board. Mr. Campbell has refrained from saying anything in this connection that would lead to any argument or criticism.

Another thing which occurs to me is this; a good system, whether manual or automatic, should be one that is available for all people, for the illiterate and for the blind, or for any person that can speak the language of the country in which the telephone system is operated. Now, the automatic system especially as regards the requirements for the placing or transmitting of the call, does not meet these conditions as easily or as simply as the mere act, in the manual system, of lifting the telephone from the hook. I do not know how you could handle this automatic system in the dark, unless you were very familiar with the transmitting apparatus, and that is quite an essential thing, so far as its use in residences is concerned. In case of danger, fire, burglary, or anything of that kind, the mere fact that if, in the manual system, you take the telephone off the hook, attention is called to the fact that something is the matter, is of very great advantage. I read only yesterday or the day before of a case of suicide, where the information was gained from the telephone; the woman who committed suicide left the telephone off the hook and they heard her groan. That is a newspaper story, but I can imagine cases where emergencies might arise whereby attention would be called in this manner. Of course, it is a small thing, but it is worth considering in connection with automatic systems. A blind man is certainly prevented from using the automatic telephone, and we have many blind people who use the telephone.

I do not think there is much in the contention as to the rapidity of the signalling to the central office. Of course, the subscriber in working the automatic system is busily engaged in whirling around the transmitting devise to the proper point, and he does not realize the time he is consuming. While he is doing that, in the City of New York you put in a call and get an answer. That may not apply everywhere, but it applies here. Mr. Campbell says in his paper that "generally speaking" it is more profitable than the manual system. I infer from that that sometimes it is not, and I think that is quite a question. From what I have learned and seen, and I have seen quite a good deal of it, I have always considered it an expensive system to maintain; but I do find that it gives great satisfaction to the subscribers and it eliminates a good deal of difficulty in connection with the wrong number. Of course, with the automatic system, the wrong number comes right back to the customer every time. In the manually operated system the subscriber looks in the book and finds 3700 and gives 3800; he does not realize that he is making the mistake and is prone to blame it on the operator; but the fact is that the customers probably make more mistakes than the operators do.

Charles A. LeQuesne, Jr.: I ask Mr. Campbell to explain if this system can be adapted to the use of private branch exchanges in connection with city exchanges; and also, what provisions is made for handling pay station calls, and whether in using a pay station telephone, it is necessary to first deposit your coin before being able to operate the calling mechanism, and, having done so, is the coin returned if you do not get the connection?

A. R. Sawyer: In 1904 when I became connected with the Michigan Agricultural College I found a campus of 25 acres or more with about 18 buildings scattered over it and no method of communication between them. I recommended to the Board of Control the adoption of a system of communication that would facilitate intercourse between the heads of the departments and save much time, the arguments for which need not be repeated. I saw that what we needed was a telephone system which would be intercommunicating for every office on the grounds and would be cheap enough in maintenance cost so that everybody could have one. I also soon realized that most of the offices should have connection with one or both of the Lansing exchanges.

After studying the matter I decided to recommend the automatic system, which was adopted by the Board of Control after due investigation. The outcome was that we put in an automatic telephone system sufficient to accommodate one hundred telephones, with three trunk lines connected to the city exchange in Lansing. The automatic system was selected because, once installed, the management would hear virtually nothing more of it in the way of running expenses. A manual system would necessitate adding to the college pay roll at least three operators as well as at least part of a man's time to keep the exchange in order, whereas the automatic system would need only part of a man's time to keep it in shape and we would have good service twenty-four hours a day and seven days in the week. At that time neither of the exchanges in Lansing gave us satisfactory service and it was my desire if we were going to put in a system that the outcome should be satisfactory telephone service. As a result, we shortly found ourselves in possession of an automatic system with three trunk lines to Lansing and a telephone in every office on the grounds as well as in the residences of those who wished to pay the college a small fee for the privilege.

The Lansing Citizens' exchange was under the management of the Grand Rapids Telephone Company which employed an automatic system and an up-to-date automatic exchange was shortly afterward installed in Lansing. At that time the automatic company did not claim that its system was best for a small exchange, but in the light of the experience we have had, we are satisfied that by all odds the automatic exchange was the best for us.

The college electrician calls up the Lansing exchange every morning over the trunk lines to make sure that they are working satisfactorily, and spends perhaps a half hour in looking over the system; the rest of the day he is free for other duties. This test over the trunk lines is necessary because of line troubles that may have occurred and not because of defective apparatus.

I will say that some of the lines to the residences outside of the campus run through a district where wires are numerous and consequently we have had much trouble with those lines, due to imperfect insulation, crosses, etc., and at times the electrician has had to spend a good deal of time on line work. That condition, however, would exist with any system. All our campus phones are connected by means of lead covered cables in tunnels so that we have no line troubles except those mentioned above.

In my recommendation to the Board I predicted that the automatic system would require less attention than any other system, but I was not prepared for the freedom from trouble which we found in the switch room. This system calls for better line work and really puts telephone work on a higher plane.

L. C. Tomlinson: It is very interesting to note the rapid advances that have been made in the past few years in automatic telephony. The large inartistic telephone, in use a few years ago, has been displaced by the small, neat and compact telephone of the present day.

At the same time the central office equipment has passed through a series of changes. By making the units compact, the central office floor space required per 1000 lines, has been greatly reduced. The apparatus has been simplified and improved with every change. A few years ago an automatic telephone system was considered so complicated, that many telephone engineers considered it quite impracticable and were unwilling to recommend it to their clients, but the ease with which it has adapted itself to all conditions has won the hearty support of most of the progressive telephone engineers.

By the multi-office arrangement of the automatic system a telephone company may reach out and serve the sparsely settled territory, that if served by the manual system, would cause an annual loss to the operating company. Not only do these subscribers receive the same class and quality of service as subscribers whose lines enter the main office direct, but their rates are generally the same, although they are at a greater distance from the main office.

H. A. Robbins: In 1905 an automatic telephone system was installed in the main office building of the Brooklyn Rapid Transit Company, the system being designed for an ultimate capacity of 1,000 lines, but to date only 110 lines have been put in service. The purpose of this installation was

1. To secure quick communication between departments, and the several offices of the departments.
2. To relieve the general switchboard, in order to obtain better service on outside calls.

The results anticipated from the installation have been very satisfactorily realized, and a large proportion of the inter-office communication is handled over the automatic system tests having shown from 80 to 120 calls per hour over this system.

As to the operation of the system, probably 90 per cent of reported troubles, although few in number, have been in the instruments. The selectors and connectors in the exchange which might be expected to give the most trouble being almost free from trouble of any kind.

While we anticipated some trouble from cross talk due to low insulation in the exchange, the system has been free from this trouble, and the talking qualities have at all times been equal to those of our manual system. The maintenance of the system is in charge of the building electrician, and requires not more than 15 to 30 minutes of his time each day, the maintenance being almost entirely labor costs. While this system, consisting of the straight Strowger type of apparatus, has given very satisfactory results, the improvements which have been brought out in the last few years, especially the Keith primary and secondary line switches, should increase materially the possibilities of the system in large installations. I believe that the combination of the present manual system and the automatic system will be the ultimate solution of the telephone problem in our large cities.

W. Lee Campbell: The point has been made that if the "busy back" should get out of order, it would probably not be noticed, for a considerable length of time in the automatic system. The method of taking care of an automatic system is somewhat different from that usually pursued in taking care of a manually operated switchboard. I can best illustrate, I think, the method of taking care of an automatic system by referring to the method which the locomotive engineer uses in taking care of his engine. He does not sit on the engine and keep going until something breaks or something that has worked loose comes off and wrecks the train. He goes out at the stations where he stops long enough, and goes over the parts that he knows from experience are liable to work loose, or to get too tight, or to get out of order in some way, and cause trouble, and with an experienced touch here and there he keeps all the mechanism in working order. Any good mechanician having the care of a machine pursues that same policy, and any successfully operated automatic switchboard must be run on that plan. The "trouble" reports that are commonly used for recording trouble with automatic telephone switchboards divide the trouble into two classes—detected troubles and reported troubles. If the switchboard attendant does not put down more detected troubles than reported troubles, it is generally taken for granted by his supervisor that he is not giving very close attention to his duty. An automatic switchboard is provided with supervisory signals for the use of the attendant, but many of the disorders he notices simply by the sound of the machines. As you know, an experienced locomotive engineer can tell by the sound of his engine whether it is running properly or not, and an experienced automatic switchboard man, who is anywhere within hearing of an automatic switchboard, can tell instantly if there is a machine which is not working properly. If he should fail to notice it, there is always a complaint clerk, an information operator, or somebody at the office, to which the subscriber can report his trouble, just as it is sometimes necessary to do with a manual plant. If a subscriber leaves his receiver off the hook, his attention is called to it in the same way that it is in the case of the manual plant; there is a device called a " howler " connected to his line, which sends an alternating circuit of high frequency and considerable voltage through his receiver, that causes it to give forth a tone called a " howl " and calls the subscribers attention to the fact that his receiver is left off the hook.

In regard to trunk lines and private branch exchange switchboards, these are handled in a manner similar to that in use in manual practice. For instance, suppose there is a private branch exchange subscriber who has a half dozen trunk lines, for handling calls to and from his place of business; they are all given the same number, just as in manual practice, and any subscriber desiring that private branch exchange simply calls the number shown in the directory. If the first trunk is busy, he is automatically switched to the second trunk, and so on until he finds an idle trunk. The apparatus does automatically what the operator does on the manual switchboard. Of course, if all the trunks are busy, the calling party gets the "busy signal" just as he does in manual practice.

In regard to the cost of maintenance, the maintenance labor for the automatic system is undoubtedly higher than for the manual system. The cost of maintenance material, however, for the automatic system is considerably less than for the manual system. I am not prepared to say, offhand, that the following is positively true, but my recollection is that the cost of new cords alone on the manual system will more than pay for the cost of all the maintenance materials on an automatic switchboard of the same size. The additional cost of maintenance labor on the automatic system is considerably more than offset by the elimination of the operators' wages, and the elimination of these wages takes care of the higher charges on the automatic system, due to the greater first cost.

With reference to depreciation, the oldest automatic system that I know of in operation to-day is the one at Fall River, Mass., which was installed in 1901, and has accordingly been in operation about nine years. I had a letter from the manager of that system very recently and he says that it is working better now than it worked nine years ago, and that the switchboards and telephones both show very little wear. So far as its wearing qualities are concerned, he sees no reason why the system should not be good for a number of years to come. Of course, the system is considerably out of date and it may be advisable to replace it, before it wears out, with a system more modern, although no plans are on foot to do so yet.

With regard to the method of reporting fires with the automatic system, nearly every automatic system in operation is arranged so that a subscriber by making one turn of his dial can report a fire to the attendant at the central office. This attendant throws a key and simultaneously rings all of the fire alarm stations, or as many as the authorities desire to have rung, and reports the fire. The method is very similar to that in use in manual practice, with the exception that the calling subscriber has to know the number to call, in order to give the alarm. It is very common in cities where the automatic systems are in use to have fire alarms sent in through the automatic switchboards. It may be that the party on whose premises the fire occurs is sometimes too excited to be able to report it, but I have never heard of such a case.

With reference to pay stations, there are very few pay stations in operation in connection with the automatic system, and in fact there are very few pay stations in operation in any independent telephone system. The pay station with an automatic system is operated in this way: The subscriber removes his receiver from the switch hook and calls the party he wants, in the usual manner. If the party answers he then drops his coin. Until he drops the coin he cannot talk to the called party, but he can hear the called party answer him. As soon as he drops the coin, his transmitter circuit is closed and he proceeds with the conversation. If he wants "long distance," or "trouble operator" or some one to whom he should have free service, the apparatus is arranged so that it is not necessary for him to drop a coin in order to close the talking circuit.

Frank F. Fowle (by letter): Mr. Campbell's paper gives a very good perspective of the principal features of a full automatic system, up to 100,000 subscribers. This limit meets the conditions at present in all but the largest cities, so that it is fair to draw general comparisons with manual systems.

The general question of manual versus automatic systems is a many-sided, complex subject, to which full justice cannot be done in a brief discussion. It is one of those questions which can never perhaps be settled for all persons under all conditions, and for all time. On the whole, the recognition accorded to automatic systems and service is increasing, and they are coming into greater use.

There are to-day three basic systems of telephone operation; the first and earliest of these was the full manual, the next was the full automatic, and the last the semi-automatic or automanual. A comparison of these systems should embrace all questions relating to service, economics and rates, along somewhat the following lines:

1. Service
   - Transmission.
   - Reliability.
   - Accuracy.
   - Speed.
2. Economics
   - Operating. Expenses.
     - General.
     - Operation.
     - Maintenance.
   - Fixed charges.
     - Taxes.
     - Insurance.
     - Depreciation.
     - Interest.
3. Rates
   - Exchange.
     - Business.
     - Residence.
     - Special.
   - Toll.

The manual system is much the oldest of the three, dating back to the origin of the business. The oldest automatic system in service has been in use about 10 years, only. The automanual system is comparatively recent, and the only installation in the writer's knowledge is at Ashtabula, O.

Full automatic and full manual systems are generally well understood as to their principal features. The auto-manual system is a compromise between the other two. The subscriber's station equipment and the method of calling the central office are similar to the manual system; after the arrival of the calling signal at the central office the procedure is different. The subscribers' lines do not terminate in front of an operator, but any incoming call is automatically switched to the first idle operator. The operator's equipment consists of a keyboard equipped with numbered plungers or keys much in appearance like the keyboard of an adding machine; there are also lamp signals and selecting keys. There is no multiple of lines before the operator and none of the equipment used in the manual keyboard. The first idle operator receives the calling signal, takes the subscriber's order, sets up on her keyboard the number called for and presses a key which causes that number to be automatically selected. The ringing is automatic and the operator is automatically cut out of the connection, so that full privacy is insured. When the subscribers hang up their receivers, the connection is automatically cleared.

This system avoids the complicated and expensive multiple switchboard, but retains a human agency in its operation. It seems to be especially adapted to the extension of manual systems where a conversion to the full automatic is not desired. A comparison of some of the individual features of these systems will now be taken up.

SERVICE

Transmission. Efficiency of transmission is a matter of electrical design and the selection of equipment. There is fundamentally no reason why the three systems cannot be designed to have equal efficiency in this respect, but both the full automatic and the semi-automatic have an advantage over the full manual system, in avoiding the electrostatic capacity and the resistance of the multiple, including the cable and the jacks. The effect of a large multiple on transmission is an important factor, and the loss occasioned in this way can only be compensated for by selecting more efficient equipment and increasing the size of the talking conductors.

The circuits shown in Figs. 8 and 23 of Mr. Campbell's paper differ somewhat from the common repeating-coil circuit and are probably no more efficient; under some circumstances they may be less efficient; as when ordinary solid-core relay magnets are used for impedances, in place of the more efficient repeating coil or impedance coil, constructed with a properly sub-divided iron core. The effect of such core construction is to increase the apparent resistance and diminish the apparent inductance, due to the energy losses in the core.

Reliability. Full automatic service tends toward greater reliability than manual or semi-automatic service, because it depends on no human agency in its operation; it is equally ready at all times of day or night. On the other hand, it possesses some disadvantage in that it is composed of such complex apparatus and has such a multiplicity of parts and contacts.

It is conceivable, also, that in some of the most recent automatic systems, which employ line switches and substations, a sudden peak in the traffic load might exceed the capacity of the available lines and switches. Insofar as such a condition might exist, it would tend to create a public sentiment against the service. But any such condition should be only temporary, as one of the traffic problems peculiar to automatic systems is that of eliminating the danger of busy line switches and trunks. Reasonably alert supervision should disclose all such faults.

Automatic systems are of course free from interruptions due to strikes of the operators, such as have occurred with manual systems in Chicago and San Francisco. They are also less likely to suffer interruption from neighboring fires, so close as to make it impossible for operators in a manual system to remain at work; instances have occurred where smoke drove the operators from their positions.

The manner in which the upkeep of a plant is taken care of is, of course, a basic factor in the service which it gives. This is particularly true where there are so many moving parts and contacts. It would be very instructive to have a comparison of these systems on the basis of the number of contacts in a complete connection between any two subscribers in the same exchange territory.

The liability of service interruptions increases in some measure with the complexity and multiplication of contacts. This tendency can be offset in part, at any rate, by proper maintenance methods, and in particular by the adoption of the policy of frequent periodic inspections to detect the approach of troubles and faults before they cause actual interruptions. Particularly in large plants, this policy is almost indispensable to good service.

Accuracy. This is one of the important qualities of good service, but rarely attained in perfect degree in manual systems. In fact, the writer has not, in the course of visiting most of the large cities in the country, found manual service that was above criticism. The human element seems to preclude the possibility of 100 per cent of accuracy in service. Under the general head of inaccuracies we should include the following:

1. Wrong numbers.
2. False busy reports.
3. False don't answer reports.
4. False rings
5. Disconnects, or cut-offs.

All large telephone companies maintain a force to supervise and test the quality of the service. On account of the expense, it has never been the custom to verify more than a very small percentage of the total traffic; the ordinary practice in service testing or supervising does not cover more than one per cent of the whole traffic, and it is usually but a fraction of that figure. When the tests are sufficiently numerous, however, they furnish some index of the general quality of the service. Some results recently given for Chicago are as follows:

	Per cent
Calls completed without trouble	78.5
Reported " busy "	13.0
Reported " don't-answer "	3.0
Cut-offs, double connections etc	1.0
Wrong numbers, fault of operators	3.0
Wrong number given by subscriber	1.5
	100.0

These figures show that nearly one call out of every four is interfered with for some cause, or more than one in five. About one in eight is held up because of busy lines, and one in twelve is interfered with for other reasons. The " don't answer " reports, amounting to three per cent, undoubtedly include some wrong numbers. The writer finds it safe always to verify a " don't answer " by calling a second time, as in some cases the party called responds on the second call, and usually advises that the first call did not reach him. The writer has also experienced the following service: " don't answer " report on first call, " busy " report on second call, party answers on third call and advises that line was not busy and no previous call or signal had been received.

Incoming wrong number calls are also annoying to the party wrongly called. The writer's telephone number is 6,033 and he has always been annoyed with calls for 6,433; this arises in part from the difficulty of distinguishing 0 from 4, when pronounced O instead of naught. There are many other instances of confusion of vowel sounds. The remedy of course is adequately loud and clear transmission and clear enunciation of numbers. But there is also the element of operator's errors, including the misunderstanding and mis-giving of orders and misplugging in the multiple. The writer has noticed that bad service at individual telephones, particularly in the way of incoming wrong number calls, seems to vary greatly and is no doubt traceable to inefficient operators on the incoming trunk or B positions, at certain hours or on certain days.

Among the prominent causes of poor manual service are overloaded operators, especially in the " busy hour " or peak load period; inexperienced operators; over-loaded order-wires or calling circuits; poor transmission, especially on order wires, which results in misunderstanding of orders and assignments; and lack of adequate traffic supervision and analysis.

The problem of procuring, training and maintaining an efficient force of operators is one of the important and sometimes difficult problems in manual service. In large cities it is necessary to maintain a training school and in consequence there is an ever-present percentage of non-productive labor. The operating force is usually somewhat unstable and the average length of service is not high.

The auto-manual system tends to eliminate many of these difficulties, because the opportunities for error are greatly diminished. The work of the operator is concentrated upon fewer functions. The limited experience with it thus far, shows that an experienced operator can handle more than double the number of calls per hour than in a full manual system.

The full automatic system eliminates the operators' errors altogether, and in this respect should give superior service. On the other hand, it places an increased burden on the subscribers, due to the manipulation of the calling device. This burden does not appear, however, to be serious, and seems warranted if it eliminates the operators' errors in the manual system.

Both the semi-automatic and the full automatic eliminate the cut-offs due to errors in manual operation, but they tend to increase the cut-offs caused by accidental manipulation of the switch-hook by the subscriber. In these systems one depression of the hook disconnects the line, and if there is no element of time lag in the apparatus, this is likely to be annoying. A slow-acting disconnect feature seems very desirable.

Speed. Speed in operation is directly a factor in operating labor costs of manual and semi-automatic systems. The sacrifice of accuracy for speed, which is sometimes the result in manual systems when high operator loads are over-emphasized, can hardly fail to create a public sentiment of both inaccuracy and unreliability in the service. The semi-automatic system has a large advantage over manual systems in this respect, and the full automatic probably has an advantage over both, all things considered.

Rapid disconnection, especially on trunk circuits, is one of the important advantages of both forms of automatic operation. Slow disconnects reduce the circuit loads in the busy hour and generally slow up the service. The circuit loads in the busy hour are directly of prime importance in determining the investment in the trunking plant, and in toll lines.

It sometimes occurs in manual operation, that the disconnect signals fail, and in consequence a subscribers' line as well as the trunk line is sometimes tied up for considerable periods. It is conceivable of course that this may happen, with automatic operation, but is seems much less likely, owing to the positive character of the disconnect function.

Other Considerations. Coin-in-the-slot telephones and pay stations require manual operation, and in a full automatic system there is no feasible way to handle this class of service, except by introducing manual operation. This objection does not exist in semi-automatic systems.

Toll service cannot, of course, be handled on a full automatic basis. The experiments which Mr. Campbell describes in substituting automatic selection at the "inward" end of toll circuits, in place of manual operation, are very interesting. The increased circuit load in the busy hour thereby made possible, will have a very important bearing on the toll line investment and should result finally in cheaper rates. It should be noted, however, that where double checking is dispensed with, an increased amount of supervision is essential to detect and prevent fraud, either by operators or subscribers. The fact which should be made plain to the operating force is not that supervision is possible, but that it exists without cessation.

One of the objections often advanced by advocates of manual systems against automatic operation has been the seeming difficulty of joining automatic with manual operation in the same plant. This difficulty exists to some degree, but manual operation in toll service will always be necessary and in toll boards designed for operation with automatic local service exclusively the objection seems more imaginary than real. It has not at least proved an insuperable objection in some of the instances where it has been tried.

OPERATING EXPENSES AND CHARGES

Operation. The cost of operation, including operating labor, supervision, rent, light, heat, etc., would seem to decrease in the following order: manual, auto-manual, automatic. Labor is the largest item in this account and the saving in labor costs is of basic importance.

Maintenance. The cost of maintenance may vary considerably even in similar plants equally situated. The efficiency of maintenance is directly a factor in the quality of service, and comparisons are therefore difficult to draw. The character of equipment to be maintained in the respective systems is quite unlike. It has been urged against automatic systems that the cost of maintenance would prove excessive, but given well built and properly installed equipment it is not apparent why this should be so. In fact a comparison between automatic and manual systems does not appear to the writer to offer a very decided choice either way.

Fixed Charges. On the general question of fixed charges, the first consideration is the investment. This in a large measure fixes taxes, insurance and interest. Automatic office equipment costs more than manual, but the distribution system less. Approximately 75 per cent of the investment in a manual system is in the outside plant or distribution system. The saving which results from the use of substations, placed at about 75 per cent in residence territory, is almost certain to prove a substantial ultimate economy in favor of automatic operation. There will be further economies in the trunking plant, brought about through higher circuit loads, with automatic operation and secondary line switches.

The insurance risk on a well engineered telephone plant is low, and the rate should not differ materially in any of the systems. If it varies at all it should probably be slightly higher on manual equipment; the steel cords which are now in wide use have sometimes started fires. This, however, has led to the practice of introducing lateral and transverse fire bulkheads in manual boards to reduce the hazard.

The annual charges for a depreciation reserve fund are determined by the investment and the useful life of the plant. More properly it is the cost of reconstruction instead of the investment, labor and materials costing the same. Automatic and auto-manual plants have not been long enough in service to determine their useful life with reasonable accuracy. The oldest automatic plant in service is about 10 years old, but there are few manual plants that are much older, counting from the date of construction or last reconstruction. The effects of obsolescence and inadequacy have been prominent in the depreciation of telephone properties, because of the very rapid expansion of the business and the frequent advances in the art. For the same reasons depreciation will probably continue to be high, in the case of automatic plants at least. However, there is a growing recognition of the necessity of sound engineering, and plants to-day are more intelligently planned and better constructed than they were formerly. The results of this will inevitably diminish the rate of depreciation, as time goes on. The useful physical life of a well engineered plant ought to be very much in excess of 10 years, with the exception perhaps of some rural systems.

RATES

It seems pretty clear that, aside from any unforseen contingencies, a modern automatic plant should be able to offer lower rates than a manual system, and should in consequence produce a greater development. The important advances in the automatic art are comparatively recent however, and rates do not seem to have been materially affected as yet.

The history of telephone rates shows that in the early days there was no scientific basis of rate making, but rates were fixed at what it was thought the traffic would bear. In many instances they were exhorbitantly high, and consequently suppressed development and stimulated competition. The competitive movement placed rates in many instances too low again, because there was no scientific analysis of cost.

To-day, the generally accepted theory, or the theory toward which we are tending as a whole, is the cost-of-service-plus-a-fair-profit. The rates of public utility companies generally are undergoing revision, mainly downward. But this is only partly true of telephone rates; many companies after ten or fifteen years of operation have found it absolutely necessary to raise them in order to earn no more than the legal interest rate. The failure to provide at all for depreciation and the lack of intelligent planning of the original systems and their extensions have been responsible in part for this state of affairs.

It has frequently been stated that the cost of operating a telephone system increases per unit as the system enlarges. This statement has been advanced in support of high rates in some cities. It is of course true that the unit cost of construction is higher in cities than in towns and country districts, but the greater density of development to some extent compensates for it. The aforementioned statement is somewhat misleading. The facts in the case are that the cost of a manual multiple switchboard increases in faster ratio than the number of lines, and the cost of distribution increases as the average mileage of wire per line increases. The investment in the distribution system exercises the largest single influence on the amount of the fixed charges. The average wire mileage per line increases with the area of the zone which comprises the exchange territory and within which the schedule of local rates applies exclusively to all traffic; it decreases with the density of development within this area. In large exchange areas more than one central office is a necessity, in manual systems, and where there are two or more offices there is necessarily an investment in a trunking plant. As a whole rates are higher in large exchange districts—higher in cities than in small towns. If the exchange district should be increased without limit, the cost of the trunking plant would make the rates prohibitive. Low exchange rates can be obtained by restricting the exchange area, and this principle has been recognized in at least one large city. Traffic between different exchange districts must bear a toll charge.

What effect the introduction of automatic operation will have upon this phase of the rate problem is not yet decided by any actual experience in very large cities, but in general it should result in lower rates, or, with present rates, in larger exchange areas. But as development will be increased by lower exchange rates, it appears to be desirable to reduce the rates rather than increase the size of the exchange district. The full automatic system as described in Mr. Campbell's paper is not worked out for more than 100,000 stations. This limit is already exceeded in the largest cities and further development of automatic equipment is necessary to fit such conditions. The competition between manual, semi-automatic and full automatic systems is certain to have a healthy result upon the telephone art and it is to be hoped that automatic equipment will soon be adapted for use in the largest cities, with ample margin for growth.

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THE APPLICABILITY OF ELECTRICAL POWER TO INDUSTRIAL ESTABLISHMENTS

BY DUGALD C. JACKSON

In two papers on electrical power for factory purposes which were published 14 years ago in the Journal of the Western Society of Engineers and the Transactions of the American Society of Mechanical Engineers, respectively, I set forth the status of the then rather new practice of utilizing electrical power distribution in manufacturing establishments. In this paper, I propose to describe the present status of electrical power in factories, and will point out certain remarkable changes which have arisen on account of improvements in methods of using electrical power and improvements in prime movers adapted to driving electrical generators.

A great change has arisen in the attitude of mill and works' owners toward electrical power, following the demonstration of certain of its qualities—especially those qualities which have contributed convenience in the arrangement of machinery so as to save floor space and to accelerate output, quicker speeds for machines or closer adaptation of speeds to the needs of high-grade manufacture, cleanliness in work rooms, and safety to employees. First creeping into use in manufacturing establishments as an auxiliary readily added in connection with electric crane service or to operate isolated or special features, electric power has now come to an established place, and it is needless to discuss its advantages in factory service compared with mechanically distributed power.

Whenever water power is available, but not contiguous to the most convenient factory site, electrical power is essential to the highest success of a manufacturing project, because by it the power of the water may be conveniently and reliably delivered for use in the most effective manner at the most desirable site. The power of several waterfalls may in the same manner be converged upon a single factory site, which may either be contiguous to or distant from the stream providing the power These advantages are effectively utilized by many successful manufacturing establishments; and they lie at the root of the success of the great power transmission plants constructed for the purpose of providing a general power supply. Even when water power in large quantities is available directly alongside suitable factory sites, the electrical distribution of the power may play a part of sufficient importance to enable it to supplant mechanical methods on account of its flexibility, which leaves the mill architect free to arrange his factory buildings to suit the requirements of manufacturing product, substantially untrammeled by those difficulties that always surround the transmission and distribution of power by mechanical means.

Also, in these days of perfected electrical power distribution for factory purposes, a multiple of boiler and engine rooms (or water-wheel rooms) located at various points on the premises has become not only unnecessary, but is recognized in most instances as wasteful. A single power house where electrical power is generated for distribution to all parts of the establishment provides a more convenient and economical arrangement. The recognition of this truth is to be observed in the power arrangements of manufacturing establishments in industrial communities from the Atlantic Coast to the Rocky Mountains, wherein each more important of the recent establishments has its individual electric power house built with a comprehensive eye to economy, conveniently located on the property, and therein are located the only prime movers of the establishment. Steam-driven power houses of this character may be located on the most favorable part of the property for the receipt of coal and supplies and the disposal of ashes, and with a proper eye to prevent inconvenience in the manufacturing processes from the smoke and dirt that ordinarily accompany the processes of generating steam power.

In a similar manner the old and ineffective plan of dividing water-wheels amongst several power houses along a canal, where large amounts of power are to be used in an establishment, and adapting the factory buildings to the locations of these power houses—a plan characteristic of many of the older textile mills of New England—may now be replaced by the much more effective arrangement with a single water-driven electric powerhouse located at the most advantageous hydraulic position on the canal. The factory buildings may then be grouped and arranged as best suits the requirements of economical manufacturing, without limitations caused by inflexible mechanical means for distributing the power. By the electrical distribution, the power may be put wherever it is needed with convenience, economy, cleanliness and safety, and to any amount needed.

Advantages are thus derived from both the manufacturing aspect and the aspect of power generation *per se* from utilizing electrical power distribution in connection with important industrial plants. Steel works, with their valuable by-product of gas-power from blast-furnace gases, make striking instances of the use of comprehensive, unitary, works' power-generating plants under conditions which formerly would have required at least several power plants scattered about the works. These are striking instances illustrating the present tendency, but many similar illustrations are to be found amongst the factories in nearly every important branch of industry.

The centering of power generation into a single generating plant for any large establishment is accompanied by economies in power generation that are of themselves appreciable, besides contributing to reliability. The question that I wish particularly to bring to your attention is: how far should such concentration proceed?

Without the electrical distribution of the power, such concentration could not be adequately carried out at all. Moreover, whatever limitations still exist toward improving the economy by completely concentrating the power generation in any industrial establishment, exist with respect to the prime movers and not with respect to the electrical distribution of the power. Where hydraulic prime movers are to be considered, the concentration may ordinarily be made as complete as the conditions of the water supply will permit, since the charges on account of first cost of installation and the labor cost of operating practically dominate the cost of the power developed, and these may ordinarily be expected to decrease per unit of output as the capacity of the plant is increased, under conditions of equal or improved load-factor.

An equivalent condition has not heretofore existed where steam prime movers have been used. Since neither labor cost nor steam economy are much improved by increasing a steam-electric generating plant over a size of a few thousand kilowatts capacity when reciprocating engines are used, the need of extreme concentration of individual plants has not heretofore been acutely felt. But the advent of large steam turbines has altered the conditions. Plants equipped with these machines installed in association with boilers provided with adequate labor-saving appliances may be operated with labor costs that vie with the labor costs pertaining to hydraulic generating plants equipped with machines of equal size; and the steam economies derived from the newer steam turbines are remarkably satisfactory. As this paper is limited by the program-makers to an introduction to the more specific papers on electrical power for industrial establishments, I cannot here enter upon a discussion of steam-turbine economies and their influence on the generation of electrical power for manufacturing establishments; but my purpose is fulfilled by emphasizing the fact that the operating economies of large steam-turbine plants, either in respect to the use of labor or the use of fuel, do not seem to be exhausted within the limits of capacity yet attained in even the largest generating plants now in commission. Moreover, the first cost per kilowatt of capacity of plant, including land, buildings, and machinery, falls off in an important degree for the larger steam-turbine plants, until such a plant may nearly rival a hydroelectric plant in the gross cost per kilowatt-hour of energy delivered at the switchboard, through the fact that the fuel cost pertaining to the steam-turbine plant has an offset in the charges caused by larger first cost per kilowatt of capacity of hydraulic plant. Mr. Stott's curves* illustrate this point clearly.

These considerations indicate that concentration of steam-electric generating plants will afford considerable economies when the concentration is carried much further than heretofore, provided large steam turbines are utilized as prime movers. The ultimate economy cannot be reached in a single factory plant, even when it comprises several thousand horse power; and logical development leads beyond the present practice of concentrating the power units of each manufacturing establishment into an individual power plant. Economy and reliability in power service are both to be obtained by further concentrating such individual power plants located in a compact industrial center into one or more great central stations each of which provides power for a number of establishments.

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* PROCEEDINGS Amer. Inst. of Elect. Eng., Apr. 1909, p. 283.

The usual round estimate of the cost of power in machine-shops and the like is $60 per horse power per year—taking the average power during working hours, perhaps 9 hours a day on the average. The cost is probably fully that large, as the power in machine-shops seldom exceeds a couple of hundred horse power and often does not exceed one hundred horse power. The load-factor is also rather low. Under more favorable conditions, large reductions may be made compared with this figure. In the case of a mill using an average of substantially 2000 h.p., for 24 hours per day, 313 days in the year, the cost per indicated horse power per hour may be reduced to the following figures in case a good compound condensing Corliss engine is used and the boiler firing is intelligently supervised. The cost of coal is put at $4 per ton on the cars at the purchaser's siding, and it is supposed to cost 25 cents per ton of fuel to put the coal in the power-house bunkers and to dispose of the ashes. As my experience with power plants located in New England is limited, I refer to conditions in parts of the country with which I am more familiar; but the data apparently apply equally well to New England conditions.

Under the conditions referred to, the costs are substantially as follows, per indicated horse power per hour in a well-run plant:

	Cents
Fuel, oil, waste and repairs	.42
Labor	.08
Insurance (boiler, liability and fire), interest (at 8%), depreciation and taxes on power plant including building and land	.15
	0.65

This is based on horse power measured by steam-engine indicators on the engine cylinders, and (on account of power losses and other expenses) the cost may be increased 50 per cent or more for the power mechanically delivered to the centres of use in the mill; in which case the cost would correspond to a central station charge of as much as 1¼ cents per kilowatt-hour for electrical power delivered to motors of large size carefully located in the mill. When running the same plant ten hours per day instead of twenty-four, the cost would come to substantially one cent per indicated horse power per hour, and when mechanically delivered to the centers of use, the cost of the power may reach a rate corresponding to a central-station charge of as much as two cents per kilowatt-hour. In small plants and plants with a less favorable load-factor, the cost is ordinarily much higher; the illustration which I have taken relates to power generated under conditions particularly favoring a low cost per horse-power-hour for an individual industrial plant.

The mill using 10 per cent more power at the maximum than is required on the average, and operating 313 days of 24 hours each in the year, gives substantially 78 per cent annual load-factor based on an installation of a rated capacity equal to the maximum load. If the 10 per cent by which the maximum load exceeds the average is expected to be carried by the margin in the capacity of the machinery over regular rating, as it properly may be in cases where the extra load only occurs for brief periods when the mill is cold after having been shut down, or for some similar reason, the annual load-factor of the machinery is substantially 86 per cent. With a load-factor like this, a large steam turbine station can generate electrical power at a remarkably economical rate. It is three times the load-factor ordinarily pertaining to electric lighting stations.

Putting this mill on a 9-hour regime for 313 days in the year, would bring its annual load-factor down to little over 30 per cent and would increase the cost of the kilowatt-hour. The load-factors of the run of manufacturing establishments rule less than this, as the power consumption is generally subject to more variations than in the mill that I have chosen for illustration.

Even with the conditions named in my illustration, a large properly designed and built steam turbine station delivering power to a considerable number of factories ought to be able to improve a little on the power costs and add something to reliability. The requirements for heating mills and the use of steam in various manufacturing processes often make it impossible to remove the means for generating steam from the factory site, but the generation of steam for power purposes is often accomplished separately on account of the different pressures needed for the two purposes, and the separation is then a matter to be dealt with as of manufacturing convenience rather than as controlled by economy of steam generation.

It therefore seems that we have before us a certain definite character of development in the power generation for our industrial cities. Electrical distribution of power has made its way in factories of all kinds of product, on account of its adaptability to diverse requirements; that is, on account of what we commonly refer to as its flexibility. It has proved particularly advantageous on account of its ready adaptation to delivering power wherever and in whatever position the best interests of getting out product demands; on account of its joint properties of steadiness of speed and controllability of speed, which have contributed to increasing both the quantity and quality of product; on account of cleanliness, reliability and safety, which have also strongly commended its use. Its use has also ordinarily proved economical from the standpoint of cost of horse power applied to the machine shafts. The advantages of flexibility and speed-control are being constantly widened by wiser designing of motors and their appurtenances, as experience extends. Economy and reliability are being additionally provided in the improved designs and more substantial construction of new power houses. But one of the important possibilities for densely crowded industrial cities is still almost untouched. For instance, in the city of Philadelphia many tens of thousands of horse power are used for manufacturing in establishments crowded together in city blocks, and the power is developed in separate large and small power plants located, as physical conditions warrant, in each establishment and with a minimum consideration given to economy. Several (perhaps three) large steam-turbine electric power houses, located on tide water aside from the densely occupied areas and constructed with a careful eye to minimizing the cost of the kilowatt-hour, could profitably supply this power at figures corresponding with its existing cost, and at the same time release for productive purposes large parts of the very valuable space now occupied by individual factory power plants. This would also relieve the thickly occupied parts of the city from the smoke and dirt that have become seriously objectionable, and would also remove the inconveniences now relating to providing the fuel supply and discarding the refuse. Some of the advantages of concentrating the power supply for large cities were urged in the address of President Ferguson at the Frontenac Convention of the American Institute of Electrical Engineers and by President Stillwell at a meeting in New York City.* It is unnecessary for me to discuss them further here.

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* PROCEEDINGS Amer. Inst. of Elect. Eng., August, 1909, p. 1055 and May, 1909, p. 317.

Much is now being said of "city planning." Some of the proposals seem to be founded on pure altruism, but others are obviously founded on economy. The city planners of crowded industrial cities have an opportunity which joins economy with altruism in studying the applicability of electrical power from centralized generating stations to large and small industrial establishments. There is here an opportunity for the betterment of crowded larger industrial cities that ought not to be overlooked. It has its possibilities also in the smaller industrial cities. The possibilities are larger and more real than appear at first view, but the limits of the program will not permit me to enlarge upon them by illustrations and argument. I lay this before you as one of the most important and desirable ways in which the proved applicability of electrical power to industrial establishments may be utilized for the betterment of crowded factory areas.

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CENTRAL STATIONS VERSUS ISOLATED PLANTS FOR TEXTILE MILLS

BY CHARLES T. MAIN

Textile mills are in the business of manufacturing tops, yarns, cloth, carpets, or some other product for the market. The production of power required is an incident or detail, and usually the cost of power does not exceed 5 per cent of the value of the product. In selecting a location for a new mill it is important carefully to consider the source and cost of power—and in estimating the value of a mill already existing—but the power is only one item for consideration and it should not be allowed to play too important a part in the decision.

The chief items of cost entering into the product of a textile mill are usually materials and labor. It is therefore more important to locate in some place where skilled operatives in the particular kind of business to be carried on can be obtained at reasonable wages, or where there can be obtained help who can be trained, and where the cost of transportation of raw materials and finished products is relatively a small amount, than it is to seek a location where cheap power can be obtained but where the other items are lacking. A saving of 10 per cent in the cost of power would represent a saving of not over one-half of one per cent in the cost of the product. The relative importance of locating a plant with reference to cheap power increases as the ratio of the cost of power to the value of the product increases.

Most of the earlier mills were located on rivers, and it was due to such water powers as were developed on the Merrimac, Connecticut, Blackstone and other rivers that the manufacturing cities were begun along their banks.

Most of these powers within reasonable reach in New England have been outgrown, and now there is found in some of the manufacturing centres a great preponderance of steam power over water power. New centers of manufacturing on tidewater have grown up which have little or no water power, but which can obtain cheap coal and low rates for transportation, and some of the most prosperous mills are driven by steam power.

In recent years the transmission of power by electricity has made it possible to locate the mills more advantageously for construction, light, railroad facilities, etc., and has made valuable water powers which on account of their location were hitherto valueless, and has enabled the construction of central steam plants to be located at the mouth of the mines or at tidewater where cheap fuel can be obtained.

ITEMS IN COST OF POWER

It can be said generally that the cost of producing power may be divided into two parts:

1. *Independent charges*, or the part which is independent of the output, embracing fixed charges on the plant—as interest, depreciation, insurance, and taxes, and, to a certain extent, repairs.

2. *Proportional charges*, or the part which is proportional to the output, including such charges as coal, labor, supplies, etc.

In general, steam plants may be said to have low independent charges, and high proportional or operating costs.

Water-power plants are usually the reverse, with high fixed charge accounts and low operating costs.

Another item which should be mentioned as affecting the cost of power is what Dr. Steinmetz calls the "reliability-factor," which takes into consideration the spare machinery needed to insure continuous service. The charges on this spare equipment are apt to have quite a bearing on the cost of power in a central station supplying power for sale, where reliability must be one of the chief considerations, and more spare or duplicate plant is usually maintained than in a private plant.

FACTORS AFFECTING THE COST OF POWER

The chief conditions which affect the cost of steam power, are as follows:

1. Cost of fuel delivered to the furnaces.
2. Amount of power produced.
3. The load-factor in its relation to fixed charges, whether the power is continuous and uniform, or intermittent and variable.

4. The net cost of power is reduced considerably in some concerns where the waste heat of the power plant can be used in the manufacturing processes in the form of low-pressure steam or warm water.

The chief conditions which affect the cost of water power are as follows:

1. Fixed charges on the development.
2. Amount of power produced in its relation to fixed charges.
3. The load-factor in its relation to efficiency of wheels, pondage, and reservoir capacity.
4. The cost of supplementary power necessary to make up for the fluctuations of the water power, if required.

VARIATION IN COST OF STEAM POWER

Steam power costs the most per unit of power when produced in small amounts. The cost is increased for fluctuating loads, and when used for purposes where the load-factor is small. By load-factor in this instance is meant the average output in per cent of the full capacity of the plant.

Steam power costs the least per unit of power for comparatively steady continuous loads, as for paper mills and other similar industries; and the cost may be still further reduced where there is use for exhaust steam or other by-products from the plant. Such conditions as the last are found in color textile mills. Power costs the most in plants having a low load-factor with a variable load, and where there is no use for the by-products of the plant, as in a lighting or street railway plant.

Textile mills usually run about 10 hours a day, and have a comparatively low load-factor, but while the load is on, it is usually fairly steady. Public service plants usually have a load-factor somewhat lower than that in textile mills but the load is variable, which is not so favorable to economical operation as the textile load would be.

So far as we know, the net cost of steam power is the least, and the net value of water power also the least, for color textile mills of any of the important industries. This is due to the usually steady load and to the fact that the waste products from the steam plant are valuable for manufacturing purposes to those industries.

The net cost of steam power for textile mills gradually increases from the cost to the mill which can use all of the waste products which will have the lowest cost, to the case of mills making white goods where only exhaust steam for warming the building and drying the yarn in the slashers can be used. In order to give a general idea of the usual costs of power under ordinary conditions in this section of the country, an analysis of the cost of power for a station of 2,000 kw, capacity is given below. This station is similar to some which have been constructed within the last few years.

As electric drive is becoming so common in textile mills, we will assume for the basis of these costs that the stations considered below will be electric, and of 2,000 kw. capacity, composed of two 1000-kw. units. Usually there is no spare apparatus in these plants. This may be considered as fair average practice at present for textile plants, but would not be tolerated for public service plants where reliability is necessary.

In making up the cost of power, all charges have been considered except the interest charges and taxes on the cost of land. These are usually not large items in textile mills, and are variable. The cost of land for the station has also been omitted from the cost per kilowatt of the station.

In making up these costs, interest has been taken at five per cent, depreciation and repairs on the apparatus for 10-hour power at 5 per cent and on the building at 2.5 per cent, insurance and taxes at 1 per cent, making a total of 11 per cent on the apparatus, and 8.5 per cent on the building. For 24-hour power, the depreciation and repairs on apparatus is increased 2 per cent, thus making the total charge 13 per cent instead of 11 per cent. A small amount is added in both cases for incidentals.

These rates of depreciation would not be proper for a station where the manufacture of current was the main product, as for a public service plant, for newer and more efficient types of apparatus would make it necessary to discard apparatus which was mechanically good. This course would not be so necessary in a manufacturing plant where the saving of a small percentage of the cost of power is not of such vital importance as are some other considerations.

With a steam engine plant, with direct-connected generators, the cost of the plant per kilowatt of capacity is about $125.00.

The cost of power from this station with coal at about $4.25 a long ton, in the pocket, would be about $33.00 per kilowatt per year of 3000 hours, as a straight power proposition. This is equivalent to about $24.60 per electrical horse power per year, and about $21.50 per indicated horse power per year. This would be a cost of 1.1 cents per kilowatt-hour.

If steam turbines are used instead of steam engines, the cost of the station will be reduced to about $105.00 per kilowatt capacity.

The cost of power produced on steam turbines would also be reduced to about $29.50 per kilowatt-year against $33.00 for the engine plant. A part of this difference is made up from the reduced cost of the station and apparatus, and a part from the better economy of the turbines which we have assumed are using the superheated steam and high vacuum which is common practice.

If steam power were to be generated for 24 hours a day for 6 days in a week, or say 300 days a year, as for a paper mill and a few of the textile mills, the cost of power would be about $57.50 per kilowatt per year for the engine plant and about $53.00 per kilowatt per year for the turbine plant. These costs reduce to 0.80c per kilowatt-hour, and 0.735c per kilowatt-hour, respectively.

The difference in the cost for the two kinds of power is due to the fact that practically the same amount of fixed charges is spread over a much greater number of kilowatt hours. There is also some saving in coal due to the elimination of banking of fires for a large portion of the time.

For industrial plants, under consideration, the load is nearly constant throughout the operating time, which means good operating conditions.

PUBLIC SERVICE PLANTS

In a public service plant, even with the same load-factor as for the 10-hour textile mill, which would be high for most of these plants, the operating conditions would not be so favorable as in a textile mill as about the same amount of banking would have to be done, and the prime movers would have to operate at variable loads. This latter undesirable feature would not be so serious in a large station as in a smaller one, so far as the efficiency is concerned, as the variation could be more nearly cared for by varying the number of units and thus operating all of them at advantageous points.

The cost of power for this type of plant is more, other things being equal, than for a plant of the same size for a textile mill having the same load-factor. This is due to the effect of variable load towards a reduction in efficiency, and because of the greater cost of plant and consequent greater fixed charges per unit of output.

It should be borne in mind, however, that these public service plants are usually of very large size, and that their output delivered has to compete in price with the cost of power from very small stations. This would give the advantage all to the central station as far as the actual cost of making power is concerned. To the cost of making the power, the central station must add the cost of transmitting, distributing, and selling it.

These additional costs probably form a very large part of the total cost to the purchaser of the power. The distribution of power in a city is expensive, meters must be read, accounts kept, bills collected, etc. So that while a central station may deliver a kilowatt-hour at the switchboard for less than one cent, it can hardly afford to sell it for that.

Some years ago, the manager of some large public service properties, testified that the cost of power to a plant of this type could not be more than one-quarter of the gross income. A representative of another company made the statement recently that it cost his company more to meter the current for their smallest customers than it did to generate it.

Effect of Use of Waste Products From Power Plant For Manufacturing Purposes

It has been common practice for many years to use the by-products, such as exhaust steam and warm water from the steam plant, for manufacturing purposes, and for heating buildings, etc. It has been also very common practice to take steam out of the receiver, between the cylinders of a compound engine, for these purposes. In many mills all of the exhaust of simple non-condensing engines is used for manufacturing purposes.

The saving from using the exhaust of a non-condensing engine, which would otherwise go to waste, is large, because there is no additional steam required for the engine, unless the back pressure is increased. Any use of the steam is nearly all clear profit, and if all of it is used the only part left to charge to power is the difference in B. t. u. due to the difference in pressure, and the condensation in the engine cylinder and jackets.

There seems to be no good reason why in time the practice of bleeding turbines should not become as common as bleeding engine receivers.

Receiver Steam

Table I shows the amount of coal chargeable to power when certain percentages of the steam entering the high pressure cylinder are taken out of the receiver. This table takes into consideration the effects on the economy of the engine of not passing all of the steam into the low-pressure cylinder, cylinder condensation, etc. The percentages in the first column are the percentages of the steam passing the high-pressure cylinder which is taken out of the receiver for manufacturing purposes. The second column is the total coal burned and the third is the coal chargeable to power after deducting the coal chargeable to manufacturing.

TABLE I

Per cent of exhaust steam used for heating purposes	Pounds of coal per one horse power per hour. All coal charged to power	Net pounds of coal per one horse power per hour after deducting for exhaust steam used
0	1.75	1.75
25	2.06	1.50
50	2.38	1.25
75	2.69	1.00
100	3.00	0.75

If the mill did not obtain its power from steam, so that it could use the low pressure steam of the plant for manufacturing, it would have to maintain a boiler plant of sufficient size to produce an amount of steam equivalent to that bled out of the receiver. The amount of B. t. u. or its equivalent in coal chargeable to power is represented by the amount of work done by the engine, and the losses due to the presence of the engine. The cost of generating the rest of the steam is chargeable to the manufacturing processes.

Examples of Manufacturing Plants

A few examples of the reduction in cost of power due to the uses of the by-products from the steam engine plant, and the bleeding of steam from the receiver may be of interest.

In one colored cotton and silk mill, the power to run the mill was about 1800 indicated horse power and for manufacturing purposes about 25 per cent of the steam for this was required in the form of steam from the receiver.

Assuming the cost of power $33.00 per kilowatt year with no bleeding, the cost chargeable to power with 25 per cent bled continuously is $29.75. The saving is $3.23 per kilowatt-year. This was for the use of low-pressure steam alone. Probably another material saving could be made by using the overflow from the condenser for water for dyeing purposes.

In another mill where much more dyeing was done, requiring a large quantity of hot water, also a large amount of exhaust steam for manufacturing and heating, the cost of power if no steam and waste products had been used, would have been about $34.00 per kilowatt year, but when the proper credits had been allowed for items chargeable to manufacturing purposes, the cost was reduced to about $26.00 per kilowatt-year, or a reduction of about $8.00 per kilowatt-year.

In a plain or white goods mill, where no steam would be required for manufacturing, other than warming the building and slashing, the saving to be effected by using receiver steam for those purposes, would be about $2.00 per kilowatt.

About three-fifths of this, or $1.20 is for heating, and the rest for slashing; so about $1.20 per kilowatt is the amount of the reduction which could be made in heating the buildings of an industry similar to a textile mill.

There are a few plants run by simple non-condensing engines exhausting into the dye-house and if the dye-house is running full there is very little change in the boiler room whether the engine is running or not.

There is one plant run by a simple non-condensing and a cross-compound engine. The exhaust from the simple engine and the condensing water from the compound engine are all used in the dyeing, finishing, and heating. The net cost of coal for power under the two last conditions is small.

In one mill which is run wholly by water power about 12,000 tons of coal are burned annually for dyeing, finishing, and heating the buildings. If a portion, or all of this mill had been run by steam power, the waste products of the steam plant would have furnished a portion of the heat required for manufacturing purposes.

The above are fair examples of the requirements in textile mills.

THE COST OF WATER POWER

The cost of water power depends upon a great variety of factors, but the essential feature is usually the fact as to whether the combined result of all these factors is such as to make the cost of the development per horse power delivered, a reasonably small amount, so that the fixed charges shall not be excessive. In other words, the allowable cost of water power cannot be materially more than the net cost of producing the same amount of power for the same purpose in some other satisfactory manner, usually by steam.

The cost of maintaining and operating a supplementary steam plant to make up for the shortage of power during low-water, flood periods, etc., must be carefully considered as it affects the actual cost of power delivered from the hydraulic plant.

For the reason that water powers usually have high independent charges they are more valuable for use on loads with high load-factors than with low load-factors, and hence are more valuable for 24-hour power than for 10-hour power.

Many of the modern developments are of very large size and the cost per horse power of the plant is in some cases small. In the determination of the cost of power, the cost per horse power of development should not be allowed to confuse or cause misrepresentation of the actual cost of power delivered. Usually the larger the development installed, the smaller is the cost per horse power of development, but it does not follow in all cases that the cost of delivered power will be smaller per horse power.

There are usually more elements of chance and more unknown factors in a hydraulic development than in a steam plant, and these facts should be taken into consideration and properly cared for. It is the lack of consideration of some of these items that has caused some of the water power developments to get into disrepute.

On the other hand a development properly made and at a reasonable cost is a valuable asset and one which bids fair to increase in value if the price of coal increases in the future as in the past.

Variation in Value of Water Power

The value of a hydroelectric power to various industries will vary in approximately the same ratio as the cost of producing power in some other way, if considered as power, pure and simple, without taking into consideration other important items affecting the business, which are sometimes more vital than the cost of the power itself.

To illustrate the value and cost of power under different conditions, it may be well to mention the two following cases:

A price for hydroelectric power was submitted to a color textile mill, of 1.2c per kilowatt-hour. After due consideration, it was decided that the mill could not afford to accept the offer, the principal reasons being:

1. On account of the use of steam for manufacturing purposes and of the water of condensation for dyeing, the net cost of steam power would be less than the price of hydroelectric power.

2. It was considered better for the textile company to own and control its own plant, if it had the capital to build it, than to purchase current brought over many miles of pole line, and be tied up to some foreign company.

The cost of power per kilowatt at the switchboard from the hydroelectric company for the operating time of the mill was about $36.00 per kilowatt-year; and for the steam plant which the mill was proposing to install this cost was estimated at about $34.00 per kilowatt-year, but if the power had been bought from the hydroelectric company, the mill would have had to install and operate a boiler plant nearly as large as the one required for both power and manufacturing.

It was estimated that the use of the waste products from the steam plant would reduce the net cost of the power at least $8.00 per kilowatt.

In another case an offer from a hydroelectric company was made to furnish power at 1.2c per kilowatt-hour, the same price that was refused by the color textile mill. For a plain cotton mill it was decided proper to accept the offer.

The principal reasons for accepting it were:

1. 1.2c per kilowatt-hour—about $36.00 a kilowatt-year, or $27.00 an electric horse power delivered. This reduced back to one horse power equals about $23.50 per year, which was very near the estimated cost of steam power for the quantity required and at the price of coal for this particular industry.

2. The mill desired to postpone the expenditure necessary for a steam plant if it could be done without serious loss.

CENTRAL STATION BUILT BY MILLS

Steam central-station plants for the distribution of power to textile mills are being built and operated by the mills themselves to considerable extent, because it is acknowledged that a central station of large capacity can be run at less expense than several isolated plants, if considered for power only, without considering the other uses for steam and warm water. It is doubtful, however, if a central plant located at such a distance from the manufacturing processes as to make it necessary to forego the saving which can be made by the use of the waste product of the steam plant can be run as economically as several scattered plants from which low pressure steam and condenser water can be made of use. In some plants, it becomes a necessity to abandon this advantage owing to the growth of the plant and the necessity of separating the power plant from the mill.

Other advantages may be derived by the concentration of plants which warrant the change.

Nearly all of the recently built concentrated plants are for electrical transmission.

Hydroelectric Station

There are comparatively few hydroelectric plants owned by other corporations which are supplying textile mills in the North with a portion or all the power required by them.

The reasons for this are as follows:

Power costs more and can be sold at a greater price.

The power plants of textile mills are usually of a sufficient size to make them fairly efficient in fuel economy and fairly cheap to run in other respects.

There is usually no large amount of reserve machinery as the service is not severe, and as it is owned and controlled by the company itself, it can take some chances which could not be taken by a power company furnishing power to the mill.

The power plant is one of the items that goes to make up the whole plant, and is so considered. It is usually of very little trouble or care to the manager, and requires no additional salaries outside of the ordinary engineers.

The item of depreciation is not so great as it is in a central power station, for in the mill the cost of power is a small percentage of the value of the product and there is not the necessity of change so frequently in order to get the utmost economy that there is in a power station whose product is power only.

With the mill plant, there are no large charges to be made to transmission costs and losses, to selling and metering the power, to franchises, administration and other charges which are necessary and common to central power stations.

The most favorably situated and least expensive hydroelectric developments can make power and distribute it and sell it to plain textile mills at prices which will be attractive, but it will be quite difficult to sell at prices low enough to compete with the net cost of power to the color textile mills which use their steam power to the greatest advantage for power and manufacturing processes.

Surplus power which can be furnished for less than the whole year must be sold at low prices as the mill must maintain its steam plant for emergency use and run it when necessary, thus adding to the cost of purchased power the fixed charges on the steam plant, and such operating costs as may be met from time to time.

In this section of the country but few of the textile mills have purchased power from any central station either steam or hydroelectric, but in the South, it is not uncommon practice for the mill to purchase hydroelectric power.

Some of the reasons for this are as follows:

Most of the mills in the North are older than those in the South and were built previously to the time of electrical transmission of power. They were, therefore, equipped with their own power plant, either water or steam, or both, and having made the investment there is not the incentive to change, whereas a new plant might save considerable investment in power plant by the purchase of power.

Most of the Southern mills are plain white mills, requiring no large amount of steam for dyeing and finishing, and requiring also less steam for heating the mills.

The mills of the North average larger in size than those in the South, and the larger the plant, the less the cost of power per horse power other things being equal.

As a rule the northern manufacturers are more accustomed to the supervision of their power plants.

CENTRAL STEAM-POWER PLANTS OWNED BY OTHER INTERESTS

There are still fewer textile mills purchasing current from central steam plants, and the reasons for this are the same as stated for the hydroelectric stations.

The central station men claim that the mills do not know how much steam power is costing them. This may be true, in many instances, but not in all. The larger mills know the cost pretty closely.

ADVANTAGES TO PURCHASERS OF ELECTRIC POWER

Some of the advantages to the purchaser are as follows:

In a new enterprise, in which the power plant has not already been constructed, there will be required less investment for the power plant with the purchase of current, than if the power is produced by the company itself, and the manufacturing company will have more capital for other uses in its business.

Less space will be required on account of the omission of the power plant and perhaps a better arrangement of buildings can be made on that account.

There will be less care to the managers of the mill if the power is purchased than if it is produced by the mill, but in a textile mill this does not usually seem to be very serious.

The company is enabled to postpone the introduction of a power plant until some later date, and in that way is able to take advantage of any improvements in power plant equipment which might be brought about during the time that current was purchased.

For the above reasons, I should expect that a mill would be willing to pay something more than the bare cost of power if the power were purchased from outside, but the mill should determine what the net cost would be from its own power plant, taking into consideration not only the cost of power, but also the saving due to the use of low pressure steam and warm water for manufacturing purposes.

If power is purchased, there must usually be added the cost of running a boiler plant at the mill for heating and manufacturing purposes in making the comparison with the combined plant at the mill for power, heating and manufacturing purposes.

For the above reasons, the central station will have difficulty in contracting with large textile mills for power except under the most advantageous conditions for the central station and the most disadvantageous conditions for the textile mill.

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THE SUPPLY OF ELECTRICAL POWER FOR INDUSTRIAL ESTABLISHMENTS FROM CENTRAL STATIONS

BY R. S. HALE

We have heard an account of electric power plants planned for each mill to have its own plant. Now, even if the 2000-h.p. plant is of a size greater than the majority of electric central stations, nevertheless the question at once arises why should we not have a central station larger than most of those of to-day and then let the very large station supply the comparatively small plants with all the possible advantages due to size and combination. This is the question on which I shall dwell.

I am interested in a great central station and this is a very immediate and almost personal question, but the form in which the question comes to a sales manager is always whether some particular owner of a mill or factory can be persuaded to buy electricity, while the American Institute of Electrical Engineers is interested in principles rather than in particular contracts.

The general question of whether a large station can supply power more cheaply than several small ones is, however, one that hardly admits of argument. Still, in order to satisfy myself as to whether 1000- or 2000-h.p. isolated power plants for mills diverge, except in detail, from the general principles that have produced our existing central station, I asked the engineers of the construction bureau of the company with which I am associated, these questions:

1. What would be the cost of power in a station that you would build to-day to supply about 2000 h.p.

2. Suppose you had to supply the same at each of ten scattered points within a territory 100 square miles, what would the power cost from a big central station?

The point of asking for both figures from one office was to be sure that both were on the same basis: that if the cost of turbines, for instance, should be taken too low, or too high, or if the cost of labor were taken too high or too low, nevertheless the same basis would be used on both sized plants and would produce no error when comparing the two propositions.

There are, of course, two kinds of errors that we are subject to. If one man makes an estimate for both sets of conditions, then even if there are errors or omissions, as, for instance, if we have figured the price per ton of coal too high or too low, or if we have figured 10 per cent depreciation against an actual 3 per cent, or have omitted taxes altogether, still the comparison is, on the whole, correct even if both sets of figures themselves are a good deal out of the way, since they would be out of the way by the same proportion in each case.

On the other hand, if instead of comparative estimates we take actual results in plants that have run long enough to give results, we find that the comparison is never on the same basis. One man has bought turbines when the manufacturer was willing to cut prices; the other has run into quicksand in his foundations or unusual labor troubles; and although the individual figures in each actual case must be much more correct than in the estimates, yet there is no question but what accidental items affect tremendously the actual costs in individual cases, so that the comparisons based on actual correct figures are often very erroneous comparisons.

For instance, published cost figures are sometimes what would be called the engineering costs, omitting several items that should be included in the real commercial costs before dividends would be declared, but if omitted items apply to both sets of figures, the comparisons are not seriously wrong. On the other hand, we know of hundreds of 2,000- horse power plants when the actual figures over a term of years show results much higher than in Mr. Main's plants, and higher than in some 1,000- horse power or even 500- horse power plants. We cannot use such actual figures for comparison, no matter how correct each set of figures may be, because they are not on the same basis and we cannot take figures for a few well-designed plants as representing real average conditions any more than the average central station can feel sure of operating at as low costs as the best central station.

Our engineers' figures, however, are on the same basis for both small and large plants. I will not take time to present their figures in detail but they figured that ten plants of 2000 horse power each cost $980,790. per year to deliver their power, and one large plant to deliver the same power, including distribution expenses, $739,580. per year—a saving of 25 per cent.

No one should expect any other comparative results. When the Edison Electric Illuminating Co. of Boston owned plants of from 100- to 2,000- horse power capacity each in Somerville, Dedham, Milton, Newton, etc. it found it paid to abandon them and establish one big generating plant at L Street in Boston and distribute the power to outlying districts.

When the Pacific Mills in Lowell, or Swift & Company in Chicago, concentrate all power in one large power house instead of one plant for each building, it is because central station power is cheaper than small scattered plants.

It is safe to say that a good engineer who has a chance to make a saving for his clients would seldom advise a dozen small plants as against one large one.

Apparently, there can be but one answer to the question as to whether a central station or scattered plants are cheapest and yet plants such as Mr. Main has installed in his practice and even smaller ones, are still being put in occasionally instead of the user buying power from existing central stations.

The real question is not whether large stations are cheaper than small ones, but the question is: Why do not the present central stations take all the present business when it can so surely be supplied at a less cost to the community if supplied from a central station?

The question is: Why are any small plants left? The real question is not as to the facts, but as to the reasons why we do not take advantage of the facts.

Now the figures usually assumed as the cost of supplying power to a small plant are somewhat different from the prices the central stations will actually quote. The question is, therefore, not whether central station power is cheaper than power of a private plant, but whose fault is it that there should be so much difference of opinion as to the actual cost in particular cases? In my opinion, both sides are to blame. The central station has, to a large extent, failed to realize its opportunity. Also, the builders, or rather promoters, of the small plants usually figure much too low for the real commercial cost, and all of us, even when we have thought clearly ourselves, have failed to get the exact knowledge sent home to the general public.

Now why should the central stations, who are not making fabulous profits, insist on such high prices instead of giving the customer at least part of the advantage of the reductions in cost that everyone agrees ought to come with central supply.

The first thing is to analyze the actual central station figures and find where the money is going. We find on taking published figures of central stations certain large items that are nearly or entirely omitted by private plants. Billing and collecting is, for instance, a large item in central station costs.

The size of these items is obviously due to the number of small customers. On the other hand, with twenty large customers, or even one such customer, it would amount to something, yet it is practically negligible in comparison with the bills rendered. Again, for a few large plants we have figured 10 per cent loss from the central station while the actual central station of to-day reports 30 per cent. For a few large customers 10 per cent is correct and again the high figure for the existing central station is due to the number of small customers who use transformers at a poor load-factor. For a few large plants, we figure only a small distribution expense, while the actual central station spends far more for distribution than for manufacturing, and as before stated, this is because the existing central station has a lot of small customers.

The combination of big with little does not necessarily add to the cost of either and more usually saves on both. The wholesale department of Jordan, Marsh & Co., dry good merchants, is not handicapped by the retail store of the same company but the wholesale and retail departments complement each other. If a central station for a few large wholesale customers should add retail net-work and get enough income from the retail to pay all the additional costs, it would not add to the cost of supplying the wholesale, although the average cost per horse power delivered to all the customers might and would go up.

Up to within a very few years, central stations have had only a retail business, and have not realized that they did not increase distribution expenses proportionately by adding a few big customers. Up to within a few years central stations figured on their average costs of retail business and thought that the big business was a loss because it would not bring as much per kilowatt hour as their average costs. To-day, they are beginning to realize that it is per cent on investment and not cents per kilowatt-hour that means profit; but business of to-day is the result of prices of three years ago; it takes time to develop. Even to-day, however, few central stations realize the field that they should cover. Unjust critics are to a certain extent responsible for this, as central stations depend on popularity. A central station making 5 per cent on its investment from the proceeds of retail business, seeing that a low kilowatt hour price to a big mill means a 6 per cent return on the investment for that customer and an accompanying later reduction in price to its small customers, hesitates to make the price necessary to secure the large customer because the big differential furnishes an apparent argument to those who claim that central stations are favoring large customers against the small, and 5 per cent with popularity is better than 6 per cent with unpopularity, even if in the latter case the small customer is getting his price actually lower.

Central stations have been weak in not analyzing their expenses properly, but the owners of small plants have likewise failed to analyze their expenses as between their plants and the rest of their business.

When a central station figures that doubling its kilowatt hours by selling ten million more to a single customer will add to its distribution expenses as much as if it sold them to ten thousand customers, it makes a very serious error. On the other hand, it is sure that every additional piece of business added adds something to the expenses all along the line; in some cases more, in some cases less. There are a great many expenses of a business that must be paid but cannot be said to be part of the cost of any particular portion. These are what are sometimes called the general expenses, but they often have other names. For instance, the salary of the president's office boy is not obviously part of the cost of unloading coal, and yet we know pretty well that if we should unload five times as much coal as we do now, the expenses of the president's office would go up.

The cotton mill seldom figures any of the interest on its floating debt against cost of power, and yet the money tied up in the coal pile must be drawn from somewhere and must earn its interest somehow.

Each item is in itself usually small, but in some isolated cases there are often extra expenses that run into big figures.

Once I prepared some estimates for one of the best engineers we have, one of the men who is now doing things rather than engineering them. He said to me, "Hale, your estimated figures are all right so far as they go, but remember that the expenses that really count in business are those that you don't figure on." In my own department I am always tempted to figure that when I add another salesman at $100 a month, I am adding only $1200 a year to my expenses. I have, however, taught myself to remember that he will need a desk, part of the office, rent, part time of a stenographer, office boy, etc., and these all cost money. A stock exchange broker once told me that when he hired a salesman, the commissions on the business the salesman brought in must be four times his salary, otherwise the salesman was really a loss.

Now, just as central stations have figured the costs of adding large customers to their retail business too high, so the mill in its analysis has failed to remember that its power plant involved other expenses besides those it figured on.

I am perfectly willing to agree that the figures which are presented in Mr. Main's paper are correct as far as they go. We have in Massachusetts 100 to 1,000 such plants as those of which Mr. Main has given an account. What has been the cost in others? The cost in a central station we *know*, and know for large stations and small stations. We have had bed-rock experiences for 20 years with no chance to draw on the general expenses of the rest of a mill. Any expenses which we forget to figure on come out of profits; but do you not suppose that if you got at a mill whose treasurer took a pride in his weaving-room and cared little about the expense of his engine-room that you would find a good deal more charged against cost of power than Mr. Main has given as the cost in the best plants?

To bring this out, take some of these estimates of cost and consider what a promotor says if he is asked to put in a plant and sell power at his estimates. Suppose he figured 6 per cent on the money; 6 per cent is a good return year in and year out and if the promotor's figures are for the actual costs, they should show profits that would give more than 6 per cent just as often as they would show losses. But we all know what the promotor says: he is not in the business of selling power and would not want to risk his money. He knows that before the work is done there will be all sorts of extra expenses of the kind he has not figured on. He knows that if the plant is run in connection with a mill, or hotel, by anyone that is not in the power business, that all these extra expenses will come out of the general profits of the other business, while if the plant is run independently and on its own basis, it would have to stand its share. Still these other expenses must be paid before the dividends. The owner of the business usually realizes this, though not in full degree. He always says, " I am perfectly willing to pay 10, 15 or 25 per cent more for central station power than it would cost me to make it myself ". If the costs he is thinking of were his real costs, this would be foolish, but what he really means is, " In addition to the costs that my engineer or bookkeeper figures for me, I must add 10, 15 or 25 per cent for what they do not figure on ".

Now, if the engineer has included all the items, *viz.*, interest at the same rate of profit the owner wants on all his busines depreciation figured not on the time the plant might last but on the date when he will scrap it, taxes, insurance, coal, water, labor, repairs, rent, removal of ashes, loss due to noise, loss due to vibration, loss due to dirt, loss due to non-flexibility, loss due to extra cost of running overtime, extra cost for superintendence including the time spent in hiring and discharging engineers, purchasing coal and supplies, checking records, etc., etc. (these all should be added), and if after *all* the expenses are included the plant shows a less cost than purchased power, it should be put in. When an owner says he will pay 20 per cent more for purchased power than it would cost him to generate it for himself, he is really saying, " My engineer is sure to omit 20 per cent of the real costs;" and just as the actual central station of to-day has a tendency to figure costs of supplying big power too high, the actual isolated plant of to-day figures its costs too low.

The projectors of isolated plants often lay stress on the special advantages of a separate plant for some particular case. This is usually in connection with the use of exhaust steam. One of the isolated plant advocates told his client that he could use his steam three times; first, for power; second, for heating by exhaust steam; and get a third supply of heat for evaporating sugar or in chemical processes.

There is no question about the theoretical advantage of using the exhaust steam for heating, but if the practical advantage followed the theoretical then the central stations should be putting down small plants in the centres of cities and selling steam heat in local blocks. If the central stations find this does not pay, and practically every one of them has tried it at some time or other, then the chances are that it usually does not pay. The same idea applies to many of the other special cases.

A further difference between a small plant and a central station is that there is an actual difference in the thing supplied in two very important ways. One is quality of service. Theoretically, a small plant can often give as good service as a large one. Practically, the large one gives wool against cotton in many ways. The steadiness and reliability of the power in every way is, as a matter of fact, much greater for central station power. This costs more and is worth more and often the central station has not any poor service to sell at a low price. This is a special condition that is really more frequent than the question of steam heating. A business that is fully satisfied with cheap and irregular power at a low price can often make that quality of power itself better than to buy a good quality of power from the central station.

A second is that the isolated plant supply is inflexible but the central station supply is flexible. An isolated plant, if figured on depreciation of 3 per cent, must be used a quarter of a century. Even at 10 per cent, it must be used a long time; and, more than this, no plant is like the one-horse shay, it can *never* be discontinued without a loss. On the other hand, central station supply in many cases can be discontinued at the will of a purchaser on a moment's notice. In other words, with central station supply, the purchaser is free; with a plant he is tied like a serf to the investment he has put in.

It is true that this freedom for the purchaser can only be given at an expense to the central station. When the central station must be prepared to lose a customer at a moment's notice, or a month's notice, it cannot make its arrangments as economically as if it counted on running along exactly the same year in, year out, as the mill that has its own plant must do in order to make the plant pay. Part of this condition can be and is taken care of by long-time contracts. If a central station can figure that its investment for a particular customer will be used for all time and will not be discontinued at some definite or indefinite date, it can supply power more cheaply. On very large business, it must get this assurance by long-time contracts; on small business by its own judgment of the future; but even with the longest and strongest contracts made with the central station, the mill is freer when purchasing power than with its own plant, since at the end of the contract it discontinues without loss, while with a plant of its own it can never discontinue without loss. Perhaps in special cases this freedom may not be worth anything, yet it is safe to say that in general the central station sells better power and allows more freedom than the isolated plant can give.

To summarize:

1. Central station power can, except in very unusual and special cases, be supplied more cheaply than when a man in another business attempts to make power as well as to carry on his own business.

2. Central station power is practically always better and gives the private owner more freedom and flexibility than when he ties himself to his plan.

3. The existing central stations have in the past figured the cost of their power supply in large lots too high, and have unconsciously hurt themselves and the public by attempting to charge large customers too much.

4. When central stations have made proper prices, the people who do other kinds of business have hurt themselves and the public by figuring their own costs of power too low and not charging their own time and general expense against the added business responsibility of the plant.

In future, the central stations will come closer to the other businesses; all will get together and pull together, and an isolated power plant will, before many years, be just as scarce as an isolated plant for making gas is to-day.

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ILLUMINATION FOR INDUSTRIAL PLANTS

BY G. H. STICKNEY

The problems of industrial illumination include the lighting of offices, yards, elevators, stairways, and other accessories, but it is the purpose of this paper to treat principally of artificial illumination for the actual processes of manufacture.

Electric light is being adopted generally as the standard of the best practice, furnishing the safest, most convenient, and usually the most economical illuminant available, therefore this paper will treat of electric lighting only.

Value of good artificial illumination. All industrial processes are subjected to a close cost-scrutiny. Pressure is placed wherever it seems possible to reduce cost. The lighting bill, holding as it does an indirect relation to the resulting product, is often discriminated against. Although it is seldom practicable to estimate accurately the relative values of different degrees of illumination, it is well known, however, that an average workman can do more work and better work with an illumination of suitable intensity than with a weaker light. Figures have been published which show the relative rate of production by daylight and by artificial light in particular installations. In every case the superiority of daylight has been startingly demonstrated. Unquestionably in the majority of manufacturing plants to-day, raising the standard of illumination would justify its cost, in the improved quantity and quality of production. Many factories are operating by old and inefficient methods, where the use of modern apparatus and methods would actually show a reduced operating cost with improved illumination.

In revising the lighting of plants to take advantage of new developments, the manufacturers have in a number of instances expressed surprise at the marked improvement in production due to the better illumination.

The workman. The operative is an important factor for consideration in any lighting proposition. Since the light is provided primarily for his use, in order that he may perform his work advantageously, it follows that it should be suited to his needs. To be satisfactory the illumination should enable the workman to perform his work quickly and well, without excessive eye-strain. The illumination can further increase his efficiency by making him at ease with his surroundings, or it can render him dissatisfied.

It is seldom practicable to equal daylight, and therefore it is usually advantageous to call as little attention as possible to the artificial lighting. One of the serious objections to placing a small portable light under the control of the workman is that he is inclined to experiment with it, not only wasting his time, but often placing the light so as to produce a glare in the eyes of his fellow, workman or himself. Such an arrangement is soon followed by eye-strain, and the workman feels a desire for more light. An increased light only makes matters worse, and at the same time calls for a higher current consumption. We have revised such installations when it was possible, cutting the current consumption in two, by going to general illumination and still providing ample working illuminations.

Such a change is usually resisted at first by the workman, partly because the strained condition of the eye makes it require more light for clear vision, and partly because the workman thinks an inherent right is being taken from him. If the change can be made diplomatically, perhaps providing additional intensity for the first few days, it is not unusual that a considerable reduction can be made, and at the same time a light furnished which is really better for the employe. In making such a change the operator should understand that the new system is an accepted success elsewhere. If it is treated as an experiment and the workman's opinion asked, he is apt to become over-critical.

The building. The lighting system in any building or room should be arranged so as to fit the conditions. Likewise the building should conform as far as possible to the requirements of good lighting. The finish of a room affects the efficiency of a lighting installation considerably. A dark finish is rich and pleasing to the eye, but in a workroom it is often extravagant. Whitening the walls, pillars and ceilings of a room will produce a remarkable increase in the effectiveness of the light.

A high-studded room sometimes requires more power to light than a lower room, but it permits the use of larger units with wider spacing. This is desirable from an installation and maintenance standpoint. It is common practice to space lamps one and one-half to two times as far a part as the height above the work.

Especially in large rooms the use of low glaring lights should be carefully avoided, as the lamps brought together by perspective are distressing to the eye. The higher the lamps are hung the less the necessary precaution to avoid glare. Modern factory buildings have as large window areas as possible. While this construction increases the effectiveness of daylight, it requires a higher intensity of artificial illumination. This is partly because operators accustomed to strong day illumination require relatively strong artificial illumination, and partly because of the loss of the artificial light through windows. Where conditions permit the use of white curtains, much light can be reflected back and retained in the room.

It is well in arranging lamps in a room to favor those parts which have the best daylight, because in arranging the work the processes requiring the most light are located near windows.

General and local illumination. There are two principal ways of lighting a room; namely, by local illumination and by general illumination. Where the former method is followed, a small lighting unit is placed at each point where particular illumination is required, the remaining parts of the room depending on stray light or a low general illumination. For general illumination, the room or section is lighted by systematically placed units so arranged that all parts receive approximately the same illumination.

Relatively large lighting units are used, depending in size upon the dimensions of the room and degree of illumination required.

With general illumination the arrangement of lamps, being independent of the detail location of machinery, does not require change with rearrangement of the work. General illumination does away with temporary construction and unsightly drop-cords, and the accompanying high depreciation, and, in many cases fire-risk.

The use of drop-cords among stock shelves is especially to be deprecated, on account of the tendency to put the lamp down where there is danger of causing fire. With properly labeled shelves, a permanently installed lamp above the aisle will provide necessary illumination. When it is necessary to look under the shelves, a hand mirror can be used.

When lighting processes in an open room, general illumination can be used economically where work is concentrated, but where there are just a few widely separated points that require light the method of local illumination will be the cheaper. The choice between the two methods often depends upon the process. General illumination gives a softer and better diffused light, but will not furnish light in a deep boring as readily as a specially placed local lamp. General illumination permits the use of the most efficient illuminants, with least wiring and maintenance expense.

Processes. In order that a process may be properly illuminated it is necessary that it should be understood by the illuminating engineer. He must know how the light is to be used, in order to determine intelligently the most desirable intensity, degree of diffusion, direction, and color of light.

In a textile mill, for example, the weave room is more exacting in lighting requirements than the spinning and carding rooms. Colored goods require more light than white goods. Different types of looms have different requirements as to direction of light. In high-grade work where there is shading of colors, white light is demanded.

A very exacting problem in color lighting was for the process of shading of buttons in a large button factory. The manufacturer who had built up his reputation on careful workmanship, was sorting buttons in from 14 to 17 shades, when the ordinary observer could readily detect only 5 or 6 different shades. After experimenting with various so-called white lights, he had practically given up the possibility of illuminating this process by artificial light. With high amperage direct-current arc lamps, equipped with inverted diffusers and large opal outer globes, specially placed over the work table, satisfactory results were finally obtained. The problem was complicated by the glossy surfaces of some styles of buttons, which demanded extreme diffusion and rifted surfaces of other buttons which demanded suitably directed light.

An interesting intensity problem was presented by a leading rifle manufacturer, who was unable to obtain suitable artificial illumination on the targets of a 220-yard testing range. Measurements showed that the marksman required 25 to 30 foot-candles for satisfactory work. Daylight intenstities were running as high as 60 or 70 foot-candles, but the artificial illuminants as installed were giving only about 6 or 8 foot-candles. An equipment which gave about 30 foot-candles was installed and gave immediate satisfaction. Later they decided to eliminate daylight altogether, as the steadier artificial light gave more uniform results.

In machine shops, general illumination can ordinarily be used to good advantage, although some special operations require local lighting. Such local lighting is sometimes provided by loaning extension lamps to the workmen on check, after the practice followed with tools. This practice is often used for automatic machinery, where special light is required for setting up, though a low general illumination is suitable for regular operation. Ordinary machine-shop work requires about 3 foot-candles, though for rough work 1 foot-candle is often satisfactory, while for fine work 6 or more foot-candles may be required.

The presence of many overhead belts makes the elimination of shadows with general illumination more difficult, and also is apt to be destructive to drop-lights. Modern shops use as few overhead belts as practicable.

In a large clothing factory recently completed remarkably satisfactory results are being obtained by general illumination from tungsten economy diffusers. This suited all processes, the number and size of lamps in each diffuser being varied to meet the intensity requirements of the different departments. Some difficulty was found in seeing the seam at the middle point of a sewing machine when working on black cloth. This ordinarily would require a local lamp. Preliminary experiments with a local reflector for casting a special beam of light at this middle point indicate that this form of local lighting can be satisfactorily applied.

In drafting rooms at least 6 foot-candles should be provided on the drawing board. The selection between general and local illumination depends upon arrangement of the room and other conditions. Where local lighting is used lamps should be shaded to cut off glare, and if possible located out of the draftsman's reach over the table a little to his left.

Circuits. The circuits for feeding factory lighting are usually determined by the central station current available, or the requirements of the electric motors in the plant. Either direct or alternating current can be used to equally good advantage for lighting, except that arc lamps do not give a steady light on 25-cycle circuits. Wherever possible the voltage of the lighting circuit should be between 100 and 125, as the most efficient lamps are more readily applied to these voltages. A 220-volt, 3-wire circuit is commonly used to good advantage.

Where motor service is intermittent, affecting the voltage regulation of a local circuit, it is desirable to separate the lighting and power circuits as far as possible. In some of the largest textile mills in New England, where the supply is alternating current, the general illumination is provided by means of series direct-current arc lamps. This furnishes a white light with remarkable economy of current consumption and maintenance. Series circuits in general, however, should be avoided except when they can be safeguarded.

Careful study is usually warranted in dividing up circuits and locating switches to accommodate requirements of particular processes.

Lamps. The lamps available for industrial illumination may be considered under two classes; namely, incandescent and arc lamps.

The principle types are as follows:

INCANDESCENT	ARC
Carbon.	Enclosed carbon.
Glower.	Intensified carbon.
Tantalum.	Mercury.
Tungsten.	Luminous, magnetite.
	Flame carbon.

None of these lamps is suitable for all conditions of lighting. It is often desirable to use several types in different parts of the same plant.

Incandescent lamps are usually made up as small units, but may be combined or grouped so as to form larger units.

The carbon incandescent lamp has a high specific consumption and is economical only with very low price of power, or in small portable units. As it will stand rougher handling than any of the other forms, the carbon lamp is ordinarily used with extension cords.

Tantalum lamps are finding a considerable use in manufacturing plants, especially where direct current is available.

The tungsten lamp has practically revolutionized commercial lighting and is now being extensively adopted in industrial lighting, especially in textile mills. It is by far the most efficient of the incandescent class, and while the maintenance seems high in some cases, it is being rapidly reduced with the progress of development. Where lamps are protected from excessive vibration or shock, the tungsten is giving an exceedingly long burning life. In choosing between tungsten and tantalum, the cost of current and the size of unit desired are usually determining factors. Tungsten lamps are used singly or in groups with metal diffusers or prism glass reflectors. Where there is considerable building vibration, they are provided with spring suspensions. In equipping and arranging lamps thought should be given to determining where the light is wanted and what degree of diffusion is required. Where there are dark ceilings, all upward light is wasted, as far as lighting the process is concerned.

Enclosed-carbon arcs, both direct and alternating current, are used to a large extent in industrial lighting. They are efficient as large units and have a very low maintenance cost. For the higher grades of lighting they are often equipped with diffusers to soften the light and direct it downward at desirable angles.

The intensified enclosed arc lamp is now available for direct-current multiple circuits. It is more efficient than the corresponding capacity of the enclosed arc lamp. This lamp and the high current enclosed arc lamp are superior to all others for color selection.

The flaming arc lamp, using the so-called yellow carbons, after several years use principally as an advertizing light, is now being used to a considerable extent for the lighting of foundries, machine shops etc., where the rooms are high, and where it is desirable to hang lamps above the crane.

The characteristic distribution of this lamp as now built is particularly adapted to high buildings since the maximum light is thrown directly downward. The light is very powerful, and suited for lighting large areas when hung high. When placed too low the light would be glaring and inefficiently distributed.

Future progress. The remarkable developments of the last few years, and the remoteness of ideal efficiency, give promise of further development and improvement in illuminants. The importance of these developments in cheapening and at the same time improving the artificial illumination of industrial processes behooves the manufacturer to keep abreast of the times. It should be borne in mind that the first cost of almost every type of electric lamp is relatively small, as compared with the cost of a year's operation, so that the user can afford to take advantage of the developments, even to the extent of throwing out his old lamps and putting in new ones at reasonable intervals.

An estimate recently made in store lighting showed, that by capitalizing the saving of the next seven years the storekeeper could afford to throw away his present lamps and install a more modern type, even if he had to pay about 10 times the market price for the new lamps. There are many similar conditions existing in the field of industrial illumination.

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THE REQUIREMENTS FOR AN INDUCTION MOTOR FROM THE USER'S POINT OF VIEW

BY WALTER B. NYE

In attempting to discuss this problem I have a natural hesitation, owing to my lack of technical knowledge, but I nevertheless appreciate that possibly the point of view of that large class which pays the bills, and to which the motor is but a means to an end, may be of some interest to the designing and constructing engineers.

My experience with induction motors has been mainly in sizes ranging from 50 to 500 h. p., running 24 hours a day six days a week, and the prime requisite from a manufacturer's point of vew is *continuity of operation*. I will not say that to this everything else must be subordinated, but in any industrial plant continuous operation must be maintained. To insure this the motor must be of a rugged mechanical design, with ample bearings; capable of withstanding reasonable overloads for a considerable period without undue heating; accessible so that it can be easily cleaned, and, in case of trouble, be easily and quickly repaired; and must be able to hang on and not "pull out," even under great variations in voltage. Efficiency, power-factor, and starting torque are all worthy of consideration, but are not, to my mind, as important as the points above mentioned.

To secure continuity of operation and ease of repair, form-wound impregnated coils should be used. Impregnation of coils is suggested because in many industries motors are subjected to moisture, steam, fumes, either acid or alkaline, and dust, which may be organic and which by its decomposition affects the insulation. Impregnation renders the coils much more immune to these conditions.

However good the motor may be, sooner or later repairs will be necessary, and in that case a form-wound coil is much more easily put in place than any other type. Coils should be made accurately to size, so there may be no difficulty in placing them in the slots, and there should be good mechanical connection between coils, as lack of this often leads to open-circuiting. It is also desirable to have a good terminal board, and preferably flat, flexible copper leads, so as to do away with soldered or screwed terminal connections. It would also be well to use particular care in the quality of the insulation on the copper bars in the rotor where they pass through the slots, as this would reduce the amount of labor in repairs. It is to be hoped that some better scheme may be devised for connecting the conductors to the outside rings, as bolts corrode, and it is seldom possible to remove them without twisting them off, which again occasions delay.

Bearings should be long, well designed, and filled with the best quality of babbitt. Great care should be given in designing the channels for the oil-rings to travel in, so there may be no chance for the rings to catch; and the sight-feed or overflow pipe should be piped away from the bearings, so that inspection may be given it regularly.

Shafts should be stiff, and the motor so designed as to permit of considerable overhang of the driving pulley. There is a tendency on the part of designers to increase the diameter of the driving pulley, narrowing the face in order to reduce the overhang; but at the speed at which most motors run, these large driving pulleys occasion difficulty in getting down to such speeds as are common in mill practice. In fact, the motors which so far have come under my notice have practically all had to be equipped with smaller, wider pulleys than those sent with them. This condition might as well be realized, and the motor designed for this service.

My experience has been mainly with a group drive, hence there is a chance of continual slow growth in the power requirements, and for that reason the motor should be capable of standing up to the load, even if in excess of its name-plate rating. A motor, therefore, should be designed to stand at least 25 per cent continuous overload wthout undue heating, and should be so designed as to permit of good ventilation and a ready access of the air jet in cleaning out.

Controllers, and particularly switches, should be of the oil-immersed type, doing away with fuses, thus meeting the requirements both as to fire hazard and to life, by avoiding the exposed live parts of the average jaw switch. Experience shows that auto-transformers for use in connnection with the induction motors furnished have almost invariably been too small, and after considerable trouble in endeavoring to start the motor, it has been necessary to secure larger ones. Designers may well consider this point and be more generous in their provision of capacity in these most necessary appurtenances.

In view of the various suggestions which have been made, the motor manufacturer may well say that to meet these conditions he will be obliged to increase the price of his motor. I believe to-day that motors have been re-designed to a point where there is almost no margin for the user, and as the motor is but a means to secure a desired result, the user can well afford to pay a little more for a well designed motor containing some reserve in capacity and ability to stand hard usage, and it will be found to be a paying investment in the long run.

A few words may not be amiss here as to the method of application of induction motors to the work in hand. In the business in which I am interested (paper manufacturing), we have not thought it wise to take up the application of the individual motor to the individual machine, although this has been developed quite fully by the electrical engineers. We have so far made use of group-drives, so arranging the groups as to make use of but a few standard sizes of motors, of which we always keep one or two in reserve for use in case of emergency. The standard group might be said to be that driven by a 100 h. p. motor, of which we have twenty, and for which we constantly hold two extra motors in reserve, one of them on trucks ready to be hurried to any point required. In this way, should anything occur to a motor, it can be removed and a new one slipped in its place with the loss of but a few moments, and the repairs may be made at the shop at leisure. This same practice holds good for all sizes up to 150 h.p., above which this scheme is not practicable.

DISCUSSION ON "THE APPLICABILITY OF ELECTRICAL POWER TO INDUSTRIAL ESTABLISHMENTS", "CENTRAL STATIONS *vs.* ISOLATED PLANTS FOR TEXTILE MILLS", "THE SUPPLY OF ELECTRICAL POWER FOR INDUSTRIAL ESTABLISHMENTS FROM CENTRAL STATIONS", "ILLUMINATION FOR INDUSTRIAL PLANTS" AND "THE REQUIREMENTS FOR AN INDUCTION MOTOR FROM THE USER'S POINT OF VIEW", BOSTON, FEBRUARY 16, 1910.

J. C. Parker: The first three of the five papers, *viz.*, those by Messrs. Jackson, Main and Hale, concern themselves with the question of the advantage and disadvantage of concentration in the generation of power for industrial establishments. Mr. Jackson indicates some of the advantages of concentration without, of necessity, indicating the desirability of carrying it quite so far as would Mr. Hale's recommendations which point to the generation of power by public utility enterprises exclusively. Mr. Main seems to pursue a middle course indicating that there are limitations to the concentration of power generation, while by inference, indicating that in many cases the process of concentration may be desirable. While, were the wish father to the thought, I should incline to agree with Mr. Hale, I believe that, as in all matters of human experience, the middle course comes nearer to hitting the facts.

For extreme concentration there are numerous arguments. I do not find that any of the gentlemen have emphasized one feature of the concentration, *viz.*, that of the possibility of securing expert skill and refined supervision to insure the maximum advantage from the refinements in design, which are possible in plants whether large or small. Operating refinements, on the other hand, are possible only in larger plants. Extreme refinement in engine and boiler efficiencies may be offset ten times over by the lack of attention to the loading of the equipment, the boiler drafts, etc. A plant of 25,000 or 30,000 h.p., can not only employ a higher type of operators but can readily carry the burden of a skilled engineer to supervise the operators and to systematically investigate the plant economies.

In the matter of flexibility, I incline to sympathize more with Mr. Hale's view than with that of Mr. Main, as I have had considerable experience negotiating with private plant owners and in attempting to indicate to them how they would improve their utilization of power with substantial savings. In many such cases I have found that the isolated plant is a veritable old man of the sea. Public service enterprises nowadays must, without exception, dispose of their power on a system which in some form or other is a variant of the Doherty system, of a fixed charge per kilowatt of maximum demand plus a unit charge per kilowatt-hour of energy consumption. The customer of a public service plant may, at any time, make improvements in his factory operation or motive power, whereby his maximum demand may be kept down or materially reduced, and, therefore, the fixed cost for the maximum demand is eliminated from his power bills. With a private plant on his hands this could not be done nor would it be defensible, since the investment is already made and the labor must be paid anyway, and therefore the reduction in maximum demand will not throw off anything from the fixed costs. Where on the other hand, power is purchased, the customer essentially has the advantage of a flexible and variable investment charge carried for him by a public service enterprise. It may be said that it is to the interest of the owner of a private plant in a growing concern to do everything in his power to improve his load factor by keeping down the maximum demand so as to prevent the necessity for additional investment in the power plant as the business grows. This condition, however, does not obtain in practice. Seldom in the early stages of a business development is it apparent that some little trouble in load factor improvement is justifiable, and conditions continue to follow their unrestricted bent, until the capacity of the power plant is reached. Then the cost of making changes which would improve the load factor has accumulated to such o large sum as to be quite prohibitive. The result is that the awner is compelled to extend his plant and to again mortgage himself to a bad load factor.

The same considerations apply in the matter of efficiency as in the matter of load factor already referred to. A private plant owner has, as an inducement to improve the efficiency of his power-utilizing machinery or motors, only the coal pile saving, which is probably not more than 10 per cent of the actual cost of power. If, on the other hand, he were purchasing his power under a satisfactory form of contract from an outside company, every per cent of reduction in his bills means reducing his maximum demand and his kilowatt-hour consumption alike, thereby enabling him to make the cost economy equal to the power economy.

One other phase of the matter of flexibility in the use of purchased power is that the owner of a private plant is unable to take advantage of the progress in the development of power plant equipment as distinguished from power-utilizing apparatus. Improvements have gone on at a rapid rate during the past 20 years and seem to show no abatement at present. It seems to the speaker that were he a power user he would prefer to have the opportunity to benefit by all the improvements in the art as they come along rather, than to install to-day a plant which five years from now would be of an obsolete type. These improvements can be made by the public service companies since with their multiplicity of units, some of which are always ready to be retired from commission, they can make their improvements in line with the latest development of the art.

These considerations would indicate that the manufacturer contracting for his power supply, so far from being " tied up " to some foreign company, as Mr. Main expresses it, is relieved from being tied up to what may be a bad investment, and is in a position to utilize every advance in the machinery peculiar to his own process, in motors, and, through the supply company, in generating apparatus.

The speaker does not seem able to reconcile Mr. Main's statement that "the isolated plant does not need to carry a large amount of reserve machinery, as it can take chances," with his earlier and more nearly defensible statement that "economy in power costs is not vital where power represents only five or ten per cent of the cost of running an enterprise." Surely for the same quality and dependability of service rendered, the isolated plant must carry a much larger percentage of stand-by equipment than the public service enterprise with its multiplicity of units; and economy on this score would hardly accord with the cost of a partial shut down of the manufactory.

With one other of Mr. Main's suggestions the speaker has an economic quarrel and that is with reference to the item of depreciation. The fact that the cost of power is, in a manufacturing enterprise, so small a percentage of the value of the product, is no reason why every effort should not be expended to secure the utmost economy in the power station. Pursuit of this philosophy to the logical conclusion would be to multiply by twenty each one of the 5-per cent elements entering into the value of the finished product and to thereby conclude that the manufacturing efficiency was a matter of more or less indifference altogether. A thousand dollars a year saved in the power plant is just as good as one thousand dollars a year saved in an office, a drafting room, in by-products, or any other way, and should be considered on its own merits absolutely irrespective of the percentage which it is of the whole. It is true that many owners of private plants do view the matter of plant economy as Mr. Main suggests, and this is doubtless a result of the fact that they are non-expert in the matter of power production and probably do not realize the importance of power plant economies. This fact constitutes another argument for the use of purchased as against privately generated power and also substantiates the alleged flexibility of power purchased.

The speaker's personal experience indicates very strongly the necessity for stopping centralization much short of what has obtained in the past. There is as pointed out by Mr. Main a certain class of business which a public service enterprise can not possibly hope to secure. Consider for a moment a condition which obtains in the centers of our large cities. Hotels have an all year and an all day demand for heat. Office buildings have an all day demand for heat during at least eight months of the year. If supplied with power by a public service company they must not only pay for the fuel burned in the central station, for the labor and supplies in a central station and for the power and boiler equipment charge, but they must in addition pay for the extra investment to take care of from 10 to 20 per cent drop in the feeders, for the power lost in these feeders, for the use of expensive underground mains with franchise taxes thereon, but over and above they must themselves maintain a nearly identical boiler equipment and pay for a nearly identical fuel, water, boiler room labor and boiler room supply expense, which effectually puts the public service enterprise without the pale.

There is a commercial feature involved also, and that is the fact that the man contemplating a private plant for such a service always under-estimates his coal consumption whereas, the central station company knows what its coal consumption is. If then we are to talk power purchase to a man who estimates that he can develop a kilowatt-hour on one and a half to two pounds of coal at his switchboard and supply his by-product heat thereby, and if we have to tell him that under a power purchase arrangement he will have to pay for, in addition to his coal for heating, three and a half to four pounds of coal delivered in his building in the form of electrical energy, we are practically tripling his fuel bill. Of course this is a fallacy on the part of the man talked to, but it is a condition nevertheless which all sorts of missionary effort fails to eradicate.

Some of these considerations have led the concern with which the speaker is associated to do the very thing which Mr. Hale finds by a process of *reductio ad absurdum* to be an argument against the theoretical advantage of exhaust steam for heating. The Rochester Railway & Light Company is at the present time laying plans for the establishment of decentralized plants throughout the business and industrial districts of our town. These plants will consist of comparatively small and inexpensive steam turbine plants interconnected on the exhaust side and electrically feeding into our electric net work. This class of plants has one signal advantage over the central power plant, *viz.*, that they cannot possibly demand any expensive condensing equipment—that, by their very nature, these plants must be cheap and simple. One thousand kilowatts of apparatus so installed will replace 1,200 kw. of central station equipment and even irrespective of the electric feeders which they obviate will cost less than 50 per cent of what the same capacity cost in our latest and best extension of the central steam plant.

While thoroughly appreciating the experience obtained heretofore and cited by Mr. Hale, we cannot fail to recognize the principal of logic that any number of failures to prove a certain proposition do not actually disprove it. The trouble in the past has been that the decentralized plants have gone at the thing in a half-hearted way and without one tremendous advantage, *viz.*, interconnection on both the steam and electric ends, whereby, the element of diversity factor may be called into play.

Mr. Main's suggestion of the possibility of bleeding the turbines for live low-pressure steam is a most interesting one and is illuminated by a suggestion made at the Briar Cliff meeting of the Association of Edison Electric Illuminating Companies last fall, *viz.*, that turbines should be so bled for the purpose of securing the necessary pre-heating of the boiler feed. This the speaker understands has been done in some few instances and very successfully. The advantage of carrying out this suggestion is much greater in the case of a turbine plant than in the case of a reciprocating engine plant, since it permits utilizing, in the lower stages of the turbine, steam not needed for heating. In the turbine this steam is very effective in the production of power, whereas in the reciprocating engine the steam so used is operating in the least effective part of the engine cycle, owing to the disproportionate friction and engine capacity needed for extorting the last few foot-pounds of work from the steam.

In handling, during the last two years, something like 180 industrial propositions, involving the examination of many private plant schemes, the speaker has found ample confirmation for Mr. Hale's statement as to the habitual under-estimating of the cost of isolated plant power. Almost every detail is viewed in the light of an unjustifiable optimism. Investment costs such as those cited by Mr. Main are seldom recognized by the man getting up the figures for such plants. Repairs, fuel cost and depreciation rate are sadly under-estimated. It is to be hoped that some day we will have a much larger group of competent engineers undertaking consultation work in connection with small plant development—men whose experience is broad enough to lead to analyses like those by Mr. Main, which while not colored by central station prejudice, on the one hand, will be free from the predisposition to habitually advise isolated plants in preference to purchased power, as a consequence of lack of experience to correct a too optimistic system of estimating.

In closing, the speaker would like to say a few words about the besetting desire of the central station companies to secure the big business. This business is very attractive sentimentally, and for advertising purposes it is very excellent, but it is questionable whether the effort so expended is so profitable as the effort used to get the smaller business. It is true that central station companies have not done enough toward making their rate systems logical and favorable to the big plant work, but it is questionable whether the big plant is per se cheaper to supply than a number of comparatively small plants since a group of large customers will have a very small diversity factor while all other expenses of serving them with the exception of the service taps, meters and clerical work are practically identical, therefore it ensues that the large customers demand, for the same individual load factor, a greater equipment per kilowatt-hour than do the small ones, whose diversity factor may be much larger.

Charles B. Burleigh: I am inclined to feel that Mr. Jackson has touched the key-note of the present power conditions when he calls to your attention the effect of the large steam turbine on industrial development.

It has not been until within the last few years that those haveing in hand the establishment of manufacturing plants requiring the use of any considerable amount of power would not have sacrificed many other desirable manufacturing advantages to secure a location where water-power was available.

As notable examples of this, one has only to call to mind the immense manufacturing establishments located along the banks of the Merrimac, Connecticut, Kennebec and other power-supplying waterways of the country.

Had power in suitable quantity on an equally attractive basis been as readily available in the (at that time) large commercial centers located on tide-water or near large railroad centers, these locations would have undoubtedly been chosen instead of such locations as Lawrence, Lowell, Manchester, Holyoke, Lewiston, Augusta and many other inland cities so located as to necessitate the receipt of raw material and the shipment of their finished product over lines where freedom from competition, to say the least, did not tend to decrease transportation charges or facilitate the immediate movement of goods.

The last few years, however, have produced marked changes in these conditions, as stated by Mr. Jackson. The large steam turbine plant "may nearly rival the hydraulic plant in gross cost per kilowatt hour of energy delivered at the switchboard." In other words, Boston, New York, Chicago, St. Louis and hundreds of other large cities throughout the country are to-day occupying the same relation to the power consumer as though an unlimited, never failing, never varying water supply for power were at all times available, and its use for manufacturing purposes was not hampered by any abnormal developmental charge, or subject to any excessive depreciation or climatic uncertainties in order to make it available for his purpose.

These conditions, together with the comparatively recent advancement in the design and operation of high-voltage electric machinery have not only vastly increased the economical radius of both steam and hydraulic developments, but are making valuable, water privileges for power purposes which have heretofore been considered not worth developing, as well as making desirable for manufacturing purposes locations which could not previously be considered.

Due in a large measure to the foregoing conditions, the time is fast approaching, if it has not already arrived, when few if any manufacturers having use for power, in large or small quantities, within a radius of 10 or even 20 miles of a large power distributing plant, can afford to devote the necessary time, energy and capital to the production of their own power.

It is with extreme hesitancy that I limit the present radius in the above statement to twenty miles. I am not sure it should not be extended to at least 50 miles, and I have no doubt that the developments of the next few years will result in lower production and transmission costs, which will permit of even further economical extension.

Consider for a moment what these conditions are capable of doing for Fall River, where all of the many thousands of tons of coal burned per annum in her immense textile establishments have to be carted up hill at an expense of from 30 to 75 cents per ton; and also at New Bedford, where notwithstanding the fact that it is located on tide-water, over 80 per cent of all the fuel burned in the city for power purposes is teamed at an average cost of some 30 cents per ton; and at Lawrence, Lowell and Holyoke, where in each case, a central electric power plant ideally located with reference to the most economical utilization of their water-powers would not only serve their present available market, but would more than double it, and the land now occupied by canals would be made available for the location of additional manufacturing industries, while the land values and saving in canal and water-wheel upkeep would very nearly, if not quite, pay for the development, to say nothing of the immense benefit that would accrue to the several communities.

While to-day the power producer and the power consumer are practically the only ones actually interested in these conditions it will be but a comparatively short time when they will realize that a percentage of their public tax is chargeable to the street wear and traffic congestion in large cities, incident in a measure to the delivery of fuel and removal of ashes, and when the tax payer not primarily interested in the production or consumption of power begins to realize that he is obliged to contribute for the upkeep of conditions no longer necessary to the prosperity of the community, I am inclined to feel that you will see the enactment of laws, pertaining to large cities at least, which will make the so-called isolated plant less desirable and the central station even more attractive.

Mr. Main in the opening of his paper calls attention to one of the most important points in connection with the consideration of the isolated plant versus the central station and I can most heartily endorse his statements that "the cost of power in a textile mill, as well as in many other classes of manufactures, is but an incident to the ultimate result," and that "a saving of 10 per cent in the cost of power would represent a saving of not over one-half of one per cent in the cost of the product."

This being an undisputed fact, it is obvious that there are other features in connection with the production of power of vastly more importance than the cost, and we may dismiss this item of the comparison with the statement that power is available from the large steam turbine or hydraulic central station or isolated plant at costs so nearly comparable, and having so little bearing on the ultimate results as to be worthy of little or no consideration.

What then should we consider as the deciding factors?

Reliability should without question be considered of prime importance as the fixed charges in an industrial plant are continuous and any interruption to, or impairment of production represents the widest and most important variable with regard to the earnings on a given investment.

What, then, may be considered the reliability of operation of a manufacturing establishment furnishing its own power as compared with one receiving its energy from a central power plant?

Let us consider first the producing machinery; here there is no material difference in either case, and I feel that those interested will concede that motors and the interior wires and fittings are as reliable as belts and shafting, which brings us to the prime mover in the isolated plant, and the entrance to the service from the central station.

Considering the isolated plants prime mover, I feel that I am correct in the statement that no 10 per cent of the manufacturing establishments, large or small, have duplicate prime movers, while central power distributing plants have many similar units, the overload capacity of a small number of which would be equal to the full capacity of any single unit.

The average isolated power plant being but an incident to the main object of the business, is given less attention by the management than is similar apparatus in the central plant, where, on the uninterrupted economical production of power, wholly depends the success of the object of the investment made, for which reason there can be no question in regard to reliability up to this point.

But, you say, the transmission line from the central station to the point of delivery is an item of unreliability not necessary to consider in connection with the isolated plant. Let us therefore consider the central station location.

In order to equitably do this, we must give some consideration to the items of difference between the water and the steam station.

With regard to the reliability of output from the station there should be no material difference because if there be any source of anticipated unreliability from the water-power, such as high or low water, anchor ice, or any interruption to the efficiency, we may consider that in order to make it commercial it has been provided with a steam relay of such capacity as will meet any possible contingency.

The steam station is or should be so located that its source of fuel and water supply can under no conditions be interfered with, while the hydraulic station must of necessity be located with reference to water supply to which the source of fuel supply is secondary, in fact the location of the hydraulic station is comparable to the old water-operated manufacturing plant in which all other considerations in regard to location are subservient to the hydraulic conditions.

The location of the steam operated isolated manufacturing plant is selected in accordance with its market, source of supply of raw material, ease of shipment, availability of suitable help, and in some industries, on account of climatic conditions, or in other words, its source of fuel supply is of minor importance.

I feel that you will agree with me that the transmission of energy by electricity over wires permanently and substantially installed, and not liable to be affected by strikes, hold-ups, wash-outs, snow-storms, floods and other natural causes to nearly the extent that the transmission of fuel is, demonstrates this last item to be fully as, if not more, reliable than the other.

While there are many other items of minor importance emphasizing the added reliability of the central station over the isolated plant, I feel confident that in view of the foregoing you will agree with me that the item of reliability is better conserved by the central station than by the isolated plant.

Flexibility is another item worthy of consideration. This item is one of admitted superiority of the electrical drive over the mechanical drive, and as the central station drive must of necessity be electrical, the comparison of this feature can only be between the electrically operated isolated plant and the central station, and a comparison on this basis is all in favor of the central station.

If a manufacturer wished to operate say 25 per cent of his plant over time from an isolated plant, he would do so at extremely poor efficiency while if supplied from the station, power is used at maximum efficiency so far as the consumer is concerned.

Additions and alterations can be made, without in any way interfering with the continuity of operation, and changes in product and capacity have no effect on operating efficiency.

Less financing for a given output is required, and to revert for a moment to the cost item, I can perhaps best illustrate the point which I wish to bring to your attention by detailing a recent investigation I was privileged to make in this connection.

A 100,000-spindle print cloth mill was projected and the question arose with regard to the source of power. It had been considered advisable to equip the property for the electrical operation of the producing machinery and the scheme had been financed to the extent of some $1,800,000.

Carefully prepared estimates demonstrated the fact that the necessary power plant would require the expenditure of some $225,000 thus leaving $1,575,000 available for the mill and its equipment of producing machinery.

It was further estimated that 100,000 spindles should produce sufficient yarn to operate 2,400 looms, each producing 90 yards of cloth per day, having a sale value of 3½ cents per yard, resulting in a yearly production of $2,260,000 worth of finished goods at a manufacturing cost of $1,810,000 when operated from its own power plant, showing a profit of $450,000, or 25 per cent profit on the invested capital.

The operating costs on the power plant included coal at $3.50 per ton delivered in the coal pocket; 5 per cent depreciation on the machinery and 3 per cent on the buildings. The cost also included 5 per cent interest on the power plant investment and on this basis it was estimated that the power cost at the switchboard would be $22 per h.p. per 300 ten-hour days per year, or a total of $66,000 per year for power.

Figures were obtained from the local steam turbine equipped central station, located on tide water and using fuel at a cost of $3.20 per ton delivered into the boilers, of 1.5 cents per kw-hr.

The acceptance of the above proposition permits of the investment of the $225,000 allotted to the power plant in producing machinery, and it will be noted from the foregoing figures that but 5 per cent was charged against the power plant, while 25 per cent was shown as the profit on the total invested capital; therefore that proportion of the capital invested in producing machinery shows much better returns, which is a strong incentive for investing the money where it will show the greatest profit.

Contracting with the central station for power and increasing the producing machinery incident to the investment of $225,000 increases the yearly output of the mill 14⅓ per cent and the sales price of the finished goods becomes $2,583,933.

We would anticipate that our power cost had also increased, first due to the fact that we feel that it is costing us more and second that we are using more power, due to the fact that we have enlarged our mill.

In the first case we used some 3,000 h.p. and in the second case we have apparently used some 3,500 h.p. This is not the case, however, as I will attempt to explain. It is a fact that for the sake of argument we have increased our producing machinery to the extent that 500 h.p. additional capacity is required to operate it.

The textile manufacturer will tell you that his mill shows a 90 per cent load factor on the basis of ten hours operation and for the sake of argument we will take this as a basis, for when operated from his own plant, it does.

When operating at a 90 per cent load factor and paying for current by meter, however, the meter records the current consumption each instant of operation. In other words, a machine stopped and started 60 times a minute, under such conditions that the intervals of stoppage just equal the intervals of full load, would record on the meter as operating one-half minute at full load.

Tests made with curve-drawing electric meters, show that the power consumption of textile manufacturing processes, with the exception of ring spinning, average about one-half of maximum, and that the spinning averages about two-thirds of maximum. Spinning consumes about 60 per cent of the power required in a mill. The central station customer obtains advantage from these conditions, which he would not if operating his own power plant, because his investment, depreciation, coal-pile and labor are not so sensitive as his meter.

First, if all the machinery in the mill stroked together we would have a load factor when operating by meter of one half of forty per cent of 0.90 plus two-thirds of sixty per cent of 0.90, or 54 per cent, for the entire mill. But all the machinery does not stroke together, nor does it break joints (so to speak) entirely, and this feature is the result of a disputed point between the central station operator and the textile manufacturer, the former claiming that from his meter readings the textile mill seldom if ever shows a better ten hour load factor than 75 per cent while the manufacturer insists that an experience of many years has shown him a 90 per cent load factor. Again for the sake of argument we will admit that they are both right.

The central station man's tell-tale (his meter) permits no lost motion but records actual conditions, while the manufacturer's tell-tale (his coal pile) is less sensitive in taking advantage of these conditions and fails to record them. It is therefore equitable to figure on the basis of experience.

As 3,500 h.p. for 3,000 hours equals 7,835,700 kw-hr., and 75 per cent of this equals 5,876,775 kw-hr., which gives at 1.5 cents, $88,151. as our total power bill.

Now what has it cost us to do this?

1. It has cost us $22,151 per year.
2. We have sacrificed our independence.

What have we gained by this sacrifice?

1. We have increased our production $323,933 per year.
2. We have a more reliable power supply.
3. We can devote all our time and energy to our legitimate business.
4. We have no need to worry about the fuel market.
5. We can make alterations without regard to the power plant.
6. We can run any department overtime at maximum efficiency.
7. We can change the style of goods without change in our power plant.
8. We can select a location ideal to manufacture without regard to power.
9. We have made $51,809 additional net profit on our investment.
10. We have earned 27.8 per cent on $1,800,000 invested instead of earning 25 per cent as would have been the case had we installed our own power plant.

If you are disposed, however, to question the position I have taken on the load factor, pending more careful investigation of the subject, if we use the same load factor of 90 per cent we have still increased our profits by $22,405 over the use of the isolated plant on the given investment of $1,800,000.

Second, consider for a moment the mill using exhaust steam and hot water in preparation work and heating. With regard to heating, I believe I am correct in the statement that about 80 per cent of the heating of textile mills is done when the machinery is not in operation and this is the case in many other classes of manufacture, for which reason the heating can be practically eliminated from the consideration so far as the power plant is concerned.

In the most extreme case, named by Mr. Main, of saving to be effected by the use of steam as a by-product, the saving is $8.00 per kw-yr. or some 23.5 per cent. Let us add 23.5 per cent to the cost of the power in the mill I have taken as an example, under the worst conditions for comparison of 90 per cent ten hour load factor where our additional profit due to the use of central station power was $22,405 and our power cost was $88,151 per year. Our increased profit is reduced by $10,715 but we still have a profit over our isolated plant operation of $11,690.

I feel that the foregoing figures demonstrate that maximum production is the item of paramount importance to the manufacturer, which is to a large extent subservient to and dependent on reliability and flexibility, all of which are best conserved by the central station at costs at least commensurate with the results obtained.

Norman T. Wilcox: In most cases the advantages of using exhaust steam where there is a steady use for it the year around cannot be successfully questioned, although it should not be forgotten that there are some disadvantages in distributing low pressure steam over considerable areas, such as might be present in the case of the larger mill plants.

The whole trend of modern development the world over is towards centralization. The laws underlying this development are peculiarly applicable to the generation and distribution of electric energy for power and other purposes. This must ultimately result in the greater portion of power being generated in great, modern central stations. These stations can take advantage of the larger load factor and greater economy resulting from the great diversity of use for power, lighting and other purposes.

When we consider that the larger central stations are already growing into wholesale power plants, that with distributing systems complete can be installed for approximately one-third the cost per unit of a lighting system only, and that the total cost of such a complete system will be as low, probably lower, than the average mill plant of even 2,000 to 5,000 kw. capacity, we may well pause before spending money for a lot of small plants with their relatively much poorer economies.

On the other hand, it should be clearly borne in mind that investment as well as distributing losses for a wholesale modern power system will not be more than one-third of those of a lighting system only. Then again, the great advances made in the art of insulation, manufacture of cables, transformers, etc., make it possible for a modern plant of this character to generate and distribute current to mill plants with even greater reliability than that afforded by the isolated plant. In addition to this, the big central station has the practical advantage of vastly greater economy in the cost of generating current, this due to its more efficient equipment, better load factor and ability at all times to benefit from a highly skilled operating force capable of applying refinements and checks which are necessary to the attainment of the best economies.

RELAY

There are several conclusions in Mr. Main's paper with which I cannot agree. The logic of assuming that no less relay is necessary for the 2,000 kw. isolated plant than for the central station is very much open to question, as the central station will have a much larger plant and more competent force; therefore, less chance of interruption to service. The central station will require less relay equipment to furnish the same reliability of service. Modern central station distributing systems, with a 13,000-volt underground system, are as reliable as belt drives.

As most of our mills are not dead, but are progressing and growing, and some of them quite rapidly at that, is it not reasonable to assume that by a second year at least, the 2,000-kw. plant outlined in the paper will be called upon to put in a third 1,000-kw. unit, necessitating 25 per cent to 50 per cent additional investment per kilowatt of capacity? This would make the total cost per kilowatt, instead of $105, as in the case of the turbine station, $130, or possibly $150 per kilowatt of capacity.

DEPRECIATION, ETC.

When it comes to the matter of depreciation and cost for equivalent service, I fail to see why more depreciation should be charged against the better cared for central station equipment than would be allowed in the case of the mill plant. If anything, rather more depreciation should be charged for the isolated plant than for the central station equipment. This tends to increase the cost of isolated plant supply. In order to meet the competition of the central station, due to the introduction of modern apparatus, the isolated plant must also replace its machinery and accept the same or greater depreciation than the central station.

CHECKS ON PLANT, ETC.

As steam is used from a common boiler at all points in the mill yard, it is not practical to obtain such operating checks as to enable the isolated plant to even approach the net economies obtained by the central station with its larger and more economical equipment. The superior economies of the modern central station are due to constant and close hourly and daily checking, a practical impossibility with the mill plant. Omit this checking for ten days and the result is a loss of 10 per cent in the plant efficiency. A longer period will materially increase this loss. This being the result of experience in the best central stations, what must be the relative efficiency in the mill plant where these checks may not be obtained?

Cost per Kilowatt-year and Kilowatt-hour, and Effect of Load Factor on Price

Results obtained by a large central station serving textile and other industries, this station having several power feeders varying from 500 to 1800 kw. capacity in daily use, show on a 3,000-hour-year basis an average 10-hour load of not to exceed 85 per cent, and this with all the advantages of diversity factor. As this station meters its energy to the customer *at the motor* in comparing services, the 5 per cent or more loss from customer's generator through switchboard and distributing system to the motor terminals should be deducted, making the real load factor 80 per cent.

In many plants, this annual 10-hour load factor is not over 70 per cent or 75 per cent. Taking the case of the color mill, an application of the 80 per cent load factor would result in the use of 2,400 kw., making the rate slightly more than 1.4 cents per kw. as compared with the impossible 100 per cent load factor assumed with 3,000 kw. annual use and estimated kilowatt-hour price of 1.1 cents. This would be approximately correct, as the only variable in the kilowatt-year cost would be the slight difference in cost of fuel for less number of kilowatt-hours, other expenses remaining the same. Likewise if the hydraulic power at $0.012 per kw-hr. had been figured on a 2,400-kw-hr. per year use, instead of 3,000, the kilowatt-year cost for the hydraulic power would be $28.80 instead of $36, and the horse power-year reduced to $21.60. Similarly, the kilowatt-year cost of $36 is reduced to 2,400 kw-hr. × $0.012, = $28.80, and the $27 per horse power is reduced to $21.60. These examples illustrate the danger of not clearly distinguishing between terms of capacity and actual work done and to be paid for by the customer.

Central station power at a definite price per kilowatt hour is a known quantity, not an estimate, and is easily checked from day to day, and for each department if desired; but cost of power to the isolated plant is an unknown quantity with cost depending largely on the varying personnel of the mill staff, as well as relatively poorer attainable efficiencies and other factors.

In order to obtain the insurance of service and price incident to the supply obtained from a big central station, the mill man can well afford to pay 10 per cent more than his estimated cost in order to obtain the central station supply.

In considering the price of the isolated plant and cost per kilowatt-year and per kilowatt-hour, load factors should not be predicted upon estimates based upon intermittent daily observations or special tests. If we would avoid disappointment and loss we should make the basis of comparison actual yearly operating conditions and costs, with their inevitable contingencies, including competent supervision. A few careful and consistent checks of this kind, if they were possible, would reveal that 80 per cent is a remarkably high yearly load factor, although it may appear from intermittent observation that the load factor is apparently higher. Consequently the kilowatt-hour cost of the isolated plant will prove much higher than anticipated and generally believed.

Incidentally, I believe that in the majority of cases our mill friends will ultimately realize that the central station will be able to furnish current and service which the mill men will be warranted in accepting.

H. B. Emerson: It is conceded to-day, by practically all who have studied into the matter, that the flexibility of electric power, places it as the foremost of all operating forces; and the points brought out by Professor Jackson's paper only tend to confirm this conclusion.

The matter of concentration of the generating plant, however, I believe must be decided by individual conditions. If the question involves only the laying out and building of a strictly new plant, then I most heartily favor a single generating station, with modern prime movers; also the placing of the manufacturing buildings so that the greatest economy can be obtained outside as well as inside the station. This, however, can not always be accomplished in old plants; for example, I know of a case where the plant has outgrown the original distributing potential of its station, where steam was needed in the process of manufacture too far away to economically transmit it from the station, and where both of these difficulties could be overcome more economically by building a second generating station than by adding step up transformers and a new steam plant for generating only steam for the manufacturing processes. Such cases are undoubtedly special, but engineers are destined to encounter such special cases, and they require even greater study and care in planning for the still further development of the plant, than would an entirely new plant, if the owners are to obtain the greatest return for the money they expend.

CENTRAL STATIONS *vs.* ISOLATED PLANTS

Regarding the question of whether the power should be obtained from a central station or an isolated plant for industrial purposes, I believe here, again, we can only decide after we know the conditions to be met in the individual plant, as the weight of argument will undoubtedly be in favor of the first in some cases, and of the second in others.

Mr. Main's point regarding use of exhaust steam in certain plants is well taken, and in many cases would be a predominant factor in deciding for the isolated plant.

In some plants the cost of power is a small item as compared with the other costs of manufacture, but in many plants it is a leading factor, and whether large or small it is looked after very sharply in an up-to-date plant. No official of a company is going to fool himself as regards the costs of one department by trying to hide part of them in the costs of another. To-day it is a cold business proposition, one mill or factory against another, and if a small percentage can be saved in the power department it is looked upon just as favorably as though it was saved in another department.

If the central station can make that saving to the owner of a plant, any broad minded man will let the station do it; on the other hand, the saving must be proved. The manager knows what his fuel, labor, supplies, repairs, insurance, etc., cost him, and if he finds he can produce his power for one cent per kw-hr., he will not pay a central station two cents for it.

I know of a textile plant generating its own power with turbine-driven generators and using a large percentage of the steam from the second stage of the turbine for dye house purposes, which is producing its power at less than one cent per kw-hr. including proper items for insurance, depreciation and taxes.

The figures check those given by Professor Jackson very well in toto, but are divided somewhat differently; the fuel cost being somewhat greater but the labor cost less. The saving obtained, by bleeding the turbine, also compares favorably with the saving shown by Mr. Mains' figures for the use of receiver steam.

I cannot agree with Mr. Hale's deduction regarding the use of exhaust steam. The methods employed by the central station are hardly comparable with those of the manufacturer. The central station has had to transmit its exhaust steam a considerable distance, and its use has been governed by parties not under their jurisdiction; some days (on account of cold weather) they would have a heavy call on their mains, and perhaps a few days following very little would be used. The manufacturer does not depend on his heating alone to use the exhaust, but has processes of manufacture requiring steam at low pressure, and the departments employing these processes are placed very near the power station and the drips returned to it at fair temperature. Further, if he did not have this exhaust steam to call upon he would have to furnish it from some other and more expensive source.

While I should favor the buying of power from a central station that could supply it at less or even at the same figure the isolated plant can produce it for I am, yet, to be convinced that a broad rule can be set forth to definitely decide the matter.

Lighting

I thoroughly agree with Mr. Stickney that the subject of industrial lighting deserves a great deal of study. Not only different plants require different systems of lighting, but the various departments of the same plant may require different illumination. One point which he did not mention, however, is one which was brought to my notice during some recent illuminating tests in a mill, where it was found that fully as much attention had to be given the distribution of the lighting units as to the diffusion of light.

With the same foot-candles in each case, the single tungsten drop lamps gave much more satisfactory illumination to the operatives than either the intensified arcs or tungsten clusters, owing to the better distribution of the light between the machinery. In other parts of the same mill, the intensified arc gave the better satisfaction, and in still other parts the enclosed arc was most advantageous. Where color matching was required, the dioxide vapor lamp was accepted as best adapted for the work.

A manufacturer to-day cannot afford to be without good illumination, for aside from better quality and quantity of light, there undoubtedly is a physiological effect upon the operatives which is advantageous, and the man who lays out a scheme of lighting for a factory must know not only the illuminating power of the lamps and their value, but must familiarize himself with the processes of manufacture in that plant.

Motors

Mr. Nye's expression of the requirements of an induction motor is undoubtedly to the point, but it must not be forgotten that the questions of power factor and efficiency must be reckoned with, especially in the larger installation, in order to obtain continuity of operation in the station as well as in the factory.

A motor can be too sturdy in many cases when the interest on the investment is taken into consideration, and there are two sides to the question of how much overload capacity is necessary for the manufacturer to provide in his standard motors. A great many industrial plants require practically no overload capacity in their motors, while others must have a considerable margin in the motor to meet the maximum demand required of it. It seems, therefore, that this question must be decided by the user and his engineer, and motors ordered to suit the requirements of their factory. Most of the electrical manufacturers of to-day have two types of motors, one for the first conditions mentioned above, and another type having considerably greater overload capacity to meet just the requirements stated as desirable by Mr. Nye. By having these two types of motors, better characteristics are obtained for each service than could be obtained if a single motor was designed to meet all kinds of service, and allows the customer who has the lighter work to obtain his motor at a less cost.

N. W. Dalton: In textile mills where the units require little power, the superiority of an electric drive admits of no question. Some of the conclusions derived from experience with induction motors in large plants are herein outlined. While in special cases the individual drive may be installed, with a large number of tiny motors, generally the group drive should be used.

What principles should govern the number of machines in each group?

First, as few *different* sizes of motors should be used as possible. Consideration of the requirements in the way of spare motors, repair parts, switches, wiring, etc., will make this clear. A study of the possible grouping of machinery in the different mills (carding, weaving, spinning, etc.) will show that a few motor ratings will cover all cases.

Second, as to motor speed. A large proportion of textile machinery is designed to be driven from slow running shafting and it follows that motors should be of moderate speed. The argument against this view is answered in every plant where the lower speed motors prevail. While speeds near 1000 rev. per min. may look right to the purchasing agent, the man who has to drive the slow running main shaft will make good the cost of the larger frame if the motor is wound for double the number of poles.

Floor space is too valuable to devote any of it to motor and driving belt. Motors should therefore be inverted and bolted to the ceiling at truss line.

Third, grouping of machinery should be limited to 50 or 60 h.p. Making our motors something under two tons. The reason of this limit is ease of handling. These motors can be drawn around mills yards on the ordinary wagon or truck. They will go up and down on the ordinary elevator without the use of hoisting tackle. The writer uses a hand truck for drawing motors around mills. This is merely an open plank frame with small cast wheels, the opening being large enough so that the frame can be drawn around the motor. The frame is fitted with an iron tripod. From the center of the tripod is dropped a threaded hook, while a hand-wheel with nut gives the necessary power to lift a two-ton motor from the floor, whence it can be easily drawn to its place.

Larger motors, say four or five tons, must be moved on skids with rollers. Some types of older mill floors will not stand this use and timbers must be laid for rollers, and in some cases shores used.

Spur-geared blocks are most economical of effort. Those of one ton rating weigh 80 or 90 pounds so that a man can easily place them. A pair will quickly hoist a motor in to place, while a single one furnishes the necessary power for replacing bearings and making repairs—work that does not necessitate lowering the motor. Thus by limiting the motor size we can get along with less repair apparatus, which is a great consideration in emergencies.

Fourth, while smaller motors than the largest size adopted are necessary, motors should in all cases be kept as near the largest size as possible. Smaller motors mean danger from overloading, due to shafting out of line, hot bearings, and other minor troubles. Such things are relatively unimportant in the larger sizes. Still, small sizes must be used in textile work where large areas of some kinds of machinery consume but very little power.

Reliability

While the electric machinery will cause fewer interruptions in the production of goods than almost any other part of the plant, still a stoppage of a motor or generator causes more attention than almost any other accident. All efforts towards greater reliability will be well spent, as the electric drive still has a reputation to acquire and maintain.

The greatest cause of failure in induction motors lies in the starting devices. Immunity from delay is best secured by having these entirely separate from the motors. A voltage reducing device in the motor leads is to be preferred. In case of failure it may be short-circuited and a temporary starter used, until repairs can be executed, without delaying production. When the starting device is located inside the rotating secondary, the matter of repairs may involve a considerable delay. In this limited space, and exposed to dirt and careless usage, no system of sliding contacts can ever give satisfactory performance.

The motor with internal starting resistance has a high starting torque with low starting current. The resistance of the secondary when up to speed is very low, thus giving the motor little slip. These are desirable characteristics, but they are outweighed by the matter of reliability. The lack of reliability seems to be more in the operator than in the motor, for some of these motors run several years with no delays whatever.

The device always furnished for starting is an auto-transformer with a double-throw switch. Would it not do to use a cast iron grid resistance? This is simpler, cheaper, easier to install and repair. The starting position should be held by hand against spring pressure so that the switch cannot be left in the starting position.

With the oil-immersed switch, it is best to have lock, so that the switch can not be thrown to the running point until it is first drawn into the starting position.

For sizes of 100 h.p. or less, and voltages not over 600, air-break switches are the most satisfactory. The oil switch is awkward to install and difficult to inspect. Often it has wood mounting and flexible leads. Some would not be safe to operate without the oil, so that the oil is a necessary adjunct and not a additional safeguard. The oil itself besides being a nuisance is often a source of danger, as some grades are very easily ignited after standing for some time. The air-brake switch is constantly in sight of the operator and any trouble is seen; while the oil switch often gives the first hint of trouble by refusing to work. Practically all the troubles of air-break switches are confined to burning of contacts and cutting in hinges; minor troubles which are easily repaired.

The air-break switch will prove unsatisfactory if used in sizes under 100 amperes capacity from want of mechanical strength, though it does not follow that all switches of higher rating are mechanically as strong. Switches must have a quick break attachment. This, unless carefully designed, is apt to give trouble. It should be strong and not interfere with operation of the main switch in case it gets into trouble. Carbon-break switches have not proved satisfactory.

Motors of the smaller sizes do not require any starting device but may be thrown directly on the line. The limit of size to which this method of starting may be carried depends on the connected machinery. Too sudden acceleration is destructive to belting. In general, textile machinery is disconnected from the shaft while the motor is accelerating, so that the starting torque required is light.

The second greatest cause of motor failure is due to bearing trouble. The bearing metal is babbitt except in smaller sizes where bronze is sometimes used. Experience with bronze demonstrates that it is very unsatisfactory. Where babbitt is used the air-gap should be sufficient to allow for the starting of the metal before the rotor strikes the primary. The smoke when the babbitt runs will attract the attention of the attendant and the motor can be stopped before the laminations strike. The latter will sometimes shift cutting the insulation of conductors.

Overloads are supposed to be prevented by fuses or safety devices. The exigencies of service are such that this is rarely the fact. A larger fuse is an easier solution than a little care and judgment. The real protection against destructive overloads lies in the use of a portable ammeter and the exercise of considerable vigilence by the electrical department. Motors should be capable of carrying reasonable overloads, and the behavior of those overloaded should be watched to ascertain the effect on temperature. In the factory where the writer has charge, not a single motor has been lost by destruction of windings, except where laminations shifted due to bearing failure.

A word as to motor design. Ventilating slots through the iron laminations are useless as they are promptly plugged by flyings. The cleaning of a hundred or more motors is no small task and if left for nights and Sundays will not be done. The only solution seems to be to clean while running. The rotating parts should be so designed that the air blast will clean them when motor is working. This is not universally the case with the motors now furnished.

The bearing on the pulley end of a motor should be designed so that it may be replaced in case of failure without the removal of the pulley. Pulleys have a way of rusting fast to the shaft and requiring some time to effect their removal. On some of the smaller motors an opposite effect has been noted. The pulleys work loose and destroy the key-seat in the shaft. A more liberal design of shaft and key is needed.

If paper pulleys are used they should have metal hubs. The variety having a piece of metal inserted to hold key will not stand up in hard service.

LIGHTING

Mills where a large proportion of the help consists of women operate from 7 a.m. to 6 p.m. only. The lighting hours are few in the year, but the lighting must be ample. We are practically confined to the carbon filament lamp, for the problem is to keep down the first cost of the installation. On alternating-current circuits the enclosed arc lamp with proper globes and diffusers gives so little illumination as to be out of the question, the tantalum lamp has no length of life and the tungsten lamp is too delicate and costs too much. In certain places where the cost of power enters, due to the necessity of burning lamp for long hours, 27 volt tungsten lamps are fairly satisfactory although in some instances they blacken very quickly.

Local lighting, inherited from gas lighting days, seems to be the desire of the mill from the office to the machine hand. General illumination has to be demonstrated before it will be accepted. In general this is the better form, but not universally. In some mills a compromise form has to be adopted.

In calculations of lighting, a certain, or rather uncertain, factor is introduced by the character of the flyings that collect on the lamps. In a spinning room for instance the wool flyings are easily cleaned from lamps and full illuminating power is secured. Where the flyings carry certain amounts of dyestuffs and starch, allowance must be made, as the labor of cleaning and the inconvenience caused thereby amount to more than the excess of power necessary to bring the lighting up to standard.

Running boards with wires cleated to them should never be used. Drops of incandescent lamp cord are a nuisance and should be done away with wherever possible. They should never be placed in a card room nor used to light Axminster looms. They are successful in spinning and drawing rooms.

Clusters of a cheap variety are the best solution for mill lighting. They should have heavy galvanized iron shades. The leads are protected by being carried down the iron pipe support. The shades receive the blows of ladders, poles and other long objects carried around mills and save the lamps from destruction. Where the machinery is of a class to transmit little vibration to the building, clusters may be rigidly secured. Some classes of machinery will cause the building to vibrate, no matter how heavily built. Under these circumstances it is necessary to hang cluster stems from a hook.

Three phase circuits are best for power, but for lighting, the matter of balancing is a nuisance. If we are confined to 125-volt lamps, the amount of copper in a mill 1000 feet is rather large. The best distribution appears to be a geometrical arrangement of 250-volt three-wire circuits. By arranging two single-phase circuits in quadrature and alternating each bent on the 250-volt circuit there is not the least trouble in keeping the sides of the three-wire system balanced and the circuits will balance on the three-phase sides. This easily acquired balance continues through the many changes in lighting that a growing plant affords.

H. W. Peck: These papers are much more general than I would wish. We need data regarding actual facts obtained, giving good, bad, and average performance, especially the last for the sake of the manager or investor. It is noticeable in both Mr. Jackson's and Mr. Main's papers that they give practically the best performance of the machinery which they are discussing, and state this fact, but they do not state what they have found to be, or believe to be, average performance, *e.g.*, Mr. Jackson says, " The cost is probably fully that large," and again, " The cost is ordinarily much higher "

I would suggest also that in discussions of this kind the cost and other items regarding performance be reduced to the basis of the kilowatt-hour. It is conceded by the authors that electrical distribution of power is most general, so that this basis will apply in the majority of cases. If the plant is so small, simple and compact as to make mechanical distribution a possibility—and investigation shows it has advantages—a correction factor due to these advantages can readily be applied to the determined cost of electric power at the switchboard. Thus Mr. Jackson's " Round estimate of the cost of power in machine shops and the like is $60 per h.p.-yr." becomes 3 cents per kw-hr. His costs of 0.65 cents and 1 cent per i.h.p. per hr., which he increases by 50 per cent for mechanical distribution, can with equal correctness be increased by from 50 to 70 per cent to give the cost per kilowatt-hour at the switchboard, thus enabling a direct comparison with central station power. Similarly, Mr. Main's figures for pounds of coal per horse power per hour increase from 1.75 and 3, to about 2.95 and 5.05 lb. per kw-hr. at the switchboard. The performance given on the basis of the indicated horse power per hour can be changed to a basis of a kilowatt-hour by multiplying by a factor between 1.55 and 1.7, the former for large units of, say, 1000 kw. capacity, and the other for smaller units of about 100 kw. capacity.

I would take exception to several matters in these papers as a general proposition, applying to textile mills, or to any other industrial establishment; in the first place, to the position taken that reliability is of secondary importance, and that no spare units should be considered necessary for an industrial establishment. This is certainly far more important for a small plant with only one or two units which would be very seriously crippled by the breakdown of one unit, than for a large central station with so many units that the load of any one could easily be carried by the remaining units. This gives a real factor of reliability without cost additional to what would be determined by good engineering practice as regards the amount of load normally carried by each machine. Likewise, if the power is as small a matter as five per cent of the rest of the business of an industrial establishment, it seems poor judgment to skimp on the power plant, which may cause a cessation of the other 95 per cent of the business. Both gentlemen concede the increased reliability of the larger power plants. I have in mind two comparatively small plants in Rochester where the cost for break down service from the central station during the first year of operation amounted to, in one case, 30 per cent of the operating cost of the plant; in the other case, 25 per cent. If central station service had not been available in these cases, and a spare equipment had not been provided, the business would have been practically shut down. I do not see, either, how it is possible to install these plants within such close limits of the actual requirements. In my experience with industrial plants, there is a very marked seasonal variation, and in most cases, a steady growth in power requirements. This, of course, makes the average load factor, considered over several years' time, much lower than the load factors given in these papers. In our experience, also, the lighting of the establishments amounts to from 10 to 25 per cent of the power requirements, and is of use for but short periods. This decreases the load factor much below that given in the papers.

This brings to mind another advantage which the central station possesses. Its growth has been steady but gradual and it has had the opportunity of making its additional equipment of the most modern type. This most efficient equipment can be used at the average load for the long-hour use while the less efficient and less valuable machines are operated for the peak load.

Neither paper considers the item of profit which should be earned on the power plant investment and operating capital to the same extent that it is earned on the rest of the investment —possibly 10 per cent; possibly 20 per cent; or at least to the extent of the central station profit, say 5 per cent. Mr. Main also passes over very lightly the matter of supervision on the part of the manager. I have found that the managers are required to expend considerable of their time and thought on the power problem. These managers are experts in business matters but are not engineers, and their time is expended to small advantage in power questions. In one of the cases cited above, where the breakdown service was so expensive, the manager said that he had spent about two-thirds of his time in connection with his plant.

As to the division of central station costs mentioned by Mr. Main, I would say that the production cost is about one-half; the distribution about one-third; and the general expenses, including advertising and commercial expenses, about one-sixth. In the specific case of the smallest customers who use just enough power to pay the minimum charge of one dollar, the central station companies certainly do lose money, *e.g.*, with an

8 cent kw-hr. rate for current, and a one-dollar-per-month minimum charge, the cost of maintaining and reading the meter, billing, and collecting, amounts to slightly over one dollar, while the 12½ kw-hr. may not represent more than 25 cents. For a large customer the meter costs are, of course, practically a negligible part of the total expense.

I have yet to find any industrial establishment that knows even within approximate limits the cost of its power, either in toto, or per unit. Such costs were recently promised me by one establishment, with the assurance that they had them exactly, and that it would be a simple matter to take them from the books in shape for me to use. They have since told me that it will mean several months' work to get this data, as they were quite surprised at the manner in which the costs had been entered. In this particular place they had a watthour meter on the switchboard, which in itself is quite unusual. Where they have not this means of knowing the amount of power generated the actual amount is almost invariably over-estimated.

R. D. De Wolf: In the article by Mr. Hale the writer has reached certain conclusions in regard to the use of decentralized plants, basing these conclusions on the experience met with under certain commercial and operating conditions. It should also be noted that the small plants abandoned by the Edison Electric Illuminating Company of Boston were not so situated that use could be made of the exhaust steam from the plants. As pointed out in Mr. Main's article, the mill which can use all of the waste products from the power plant will have the lowest cost; and this same condition exists when the power plant is operated by a central station company and that company is in a position to sell its waste products.

There are several conditions existing which make the operation of a decentralized heating and power plant particularly attractive. In plants of this type the operating conditions are determined not by a widely fluctuating electrical load, but by a fairly steady heating load. The heavy overloads met with in operating generating stations, lasting from one-half hour to an hour or two, are not encountered when the primary purpose of the plant is to supply steam for heating. On account of this great improvement in the load factor on a plant it is unnecessary to carry large reserve power units for peak loads, and the plant can be operated at or near its point of maximum efficiency the greater part of the time. As the plant is necessarily a non-densing plant, complicated auxiliary apparatus is dispensed with, and a simple type of machinery installed which can be operated by comparatively unskilled labor and requires less attendance. Automatic features can be included in the design of the installation, so that the plant can be operated with the minimum amount of labor per unit of output. In other words, the labor can be used as efficiently in a medium sized plant of this type as the higher grade labor is used in a much larger condensing plant.

When the plant can be so located as to handle a group of buildings of a diversified character, such, for instance, as a department store, a hotel, a theatre, an office building, and a manufacturing plant, the diversity factor of the steam load will be such that the resultant load on the plant will have only a comparatively small variation.

The type of apparatus installed in a plant of this character, as pointed out in Mr. Parker's remarks, will be comparatively simple and inexpensive. Complicated condensing apparatus will not be required, and there will be a corresponding saving in operating expense, due not only to decreased interest and depreciation charges, but to decreased repairs and supplies. With a plant of this character installed in the business district, where 250-volt direct current distributing systems are used, the high installation cost of a feeder from the distant central station is done away with, and the accompanying line losses saved. In estimating on a recent proposal I found that the approximate cost of installing a 500-h.p. non-condensing plant under such conditions was $25,000; while the cost of a duplicate plant at the central station about one-half mile away, together with the feeder cables, amounted to $94,000. Under these conditions the total operating cost and fixed charges of the non-condensing station per year was $22,590, and of the condensing station and distributing system was $25,790. The fixed charges in each case were $3,050 and $13,250.

These decentralized plants effect the distribution charges in two ways; first, the steam distributing cost; and second, the electrical distributing cost.

The advantages accruing under the heading of steam distributing costs are as follows:

1. Cost of distributing system is less, consequently fixed charges depreciation charges, and repairs are less.

2. Better distribution and better service can be given, as the distance to which steam is transmitted will not be great.

3. Condensation in the distributing system will be less, and the amount of condensed water in the mains which has to be taken care of will be correspondingly less.

4. The system as a whole can be made more flexible by means of tie lines between the different stations, or between the different distributing mains.

The attitude of the customer toward the use of steam can be decidedly influenced, due to the fact that the steam is generated in close proximity to the point at which it is required, rather than being generated at some distant point and transmitted with consequent loss of temperature and increased percentage of moisture in the steam.

The electrical distributing cost is greatly decreased as pointed out above, due to the elimination of expensive transmission lines, expensive generating units, etc.

The operation of plants of this character will enable the central station company to operate certain of its plants under those conditions which Mr. Main has found to be most economical for textile mills, *i.e.*, use can be made of all the waste products of the plant. I think that the manufacturer can be shown that the value of power and of these waste products to him are much more important than the five per cent value given by Mr. Main. If the cost of power is five per cent of the value of the product, this value being necessarily the selling price, then under average manufacturing conditions the factory cost of the product will not be more than 50 per cent of this selling price, and the power would then become 10 per cent of the factory cost. Furthermore, the cost of raw material entering into the product would probably form at least 50 per cent of the factory cost, and therefore the power forms 20 per cent of the manufacturing cost. Any economy which the manufacturer can make in his cost of power will, therefore, be an important item in his total cost of manufacture. When the central station is in a position to supply the manufacturer with all his requisite power, heat, and light, it can effect economies for him which would otherwise be absolutely impossible.

Referring to Mr. Parker's remarks in regard to the central station companies securing large business, it should be noted that they have not only been hampered in this, but that the profits which they could make from such a transaction have been limited to the profits accruing from the sale of power alone. When these large users can be supplied with the necessary steam, an additional source of profit will be introduced; and whereas the central station may have formerly been carrying a load of this character purely for its sentimental and advertising value, when the heat is supplied in addition, the load will become a profitable one.

In closing, I would like to point out one further advantage which the central station company has in handling business of this character. When a given manufacturer, whom we may call *A*, happens to be operating under conditions such that the exhaust steam from the generating apparatus required to furnish him his necessary light and power is just sufficient to give him the necessary heat and low pressure steam for industrial purposes, he will be operating under his most economical conditions, *i.e.*, the ratio between his light and power load and his heating load is one. His neighbor *B* may be operating under conditions such that this ratio is one-half; another neighbor, *C*, under conditions such that this ratio is 1½. The central station can combine these loads, furnish *A* with his total requirements at his old cost, or somewhat less, and make a considerable saving for both *B* and *C*. In this way, by using a sliding rate which will vary with the steam consumption and the ratio, the manufacturer will be enabled to effect an economy for himself by so arranging his processes of manufacture, etc., as to bring about the most economical operating condition for the central station.

Albert L. Pearson: Regarding motors, I agree in general with Mr. Nye as to the requirements which he has set forth for an induction motor, but feel that one or two points should be given further consideration.

The motor should have a high efficiency, particularly in installations where power is purchased. One per cent difference on a group of ten 100-h.p. machines means 10 h.p., the value of which is an appreciable amount to be added to or deducted from the power bill.

The power factor should be as high as possible, as the voltage regulation of the system is better, and in the case of a large installation considerable saving in copper may be made. An installation of induction motors, recently completed, shows one of the values of high power factor. The power company requires this to be maintained at 90 per cent at its measuring instruments; for anything under this it makes quite an additional charge. In this particular case a rotary condenser is used. Such a machine is fairly desirable provided about 70 per cent of its kilovolt-ampere rating can be turned into mechanical energy. In any case it is a much more troublesome machine than an induction motor, owing to complications of exciter, methods of starting, etc. The curves of efficiency and power factor should be as flat as possible to ensure the most economical operation at all loads, say from 50 per cent to 125 per cent.

The slip, or difference between synchronous and full load speed, should be small to insure, as nearly as possible, constant speed at the machines at all times. This is of special value in textile plants where one motor is used for driving four spinning frames, and in group drives for looms where close speed regulation is not only desirable but often necessary. This same thing applies to a group drive for spinning frames, but probably is not of so much importance as for the four-frame drives. In the case of individual drives this does not count for so much, as the driving gear will be arranged to meet the full-load speed of the motor.

The air gap should be reasonably large so that the motor will require a minimum amount of attention at this point. A small gap, unless carefully watched, is very apt to cause considerable annoyance from rubbing. The ventilation should be good and the ducts, etc., so arranged as to facilitate cleaning. It is desirable to have motors waterproof and the terminals enclosed, for such places as opening and picker rooms, so that all of the contents of a machine may be run out in case of fire.

In textile plants, an overload capacity greater than the standard two-hour rating is not necessary. The cost of a rating of 25 per cent overload continuously is an unnecessary investment. Unless the design is such that efficiency and power factor are their best at 80 per cent of their maximum rating, the point of ordinary operation, there will be a continuous and unnecessary loss.

Regarding the application of motors, there is no question as to the advantages resulting from individual drives, such as cleanliness from absence of overhead belting and shafting, improvement in illumination, decrease in cost of power, etc. In equipping a plant with electrical drives care should be taken that it is not "overmotored" as such a condition is sure to result in poor voltage regulation and generally unsatisfactory operation. It is often desirable to make tests after installing motors to make sure that proper machines have been selected. This applies more to the equipping of old plants where the power required is often questionable, than to new installations.

The power supply for industrial plants should never be at less than 550 volts, three-phase, 60 cycles, and very satisfactory results are being obtained from 2,080-volt motors above 20- or 25-h.p. sizes. Possibly, in the case of individual drives, where motors smaller than one horse power are used, better results may be obtained from 220 volts.

In a motor-driven plant the wiring takes the place of shafting in a mechanically driven one. This should be installed in a thoroughly first-class manner, protected from injury and so arranged that the voltage at the motor will never be lower than that at which it is rated. Fuses should never be used except on very small sizes of motors. Air-break switches should never be used. Oil switches should be as simple as possible. Current-carrying parts should be liberal, and contacts so arranged as to be easily renewed.

The first cost of motors and starting devices is too often the first consideration, rather than reliability and future operating costs. While the first cost of equipping a textile plant with motor drive may be more than for direct mechanical drive from a steam engine, this is more than offset by the reduced cost of maintenance and the convenience in operation. This is true for synchronous motors as well as induction motors, for a large number of mills in the South have been equipped with these machines using a rope drive the same as for a steam engine.

H. D. James (by letter): The papers this evening discuss the development of electric power for industrial purposes, but have very little to say about the adaptation of this power to industrial machinery. For years we have had electrical power available, we have recognized the advantages of a motor drive for smoothing out the load curve; then why is it that we did not long ago develop this market for power?

The writer believes that this development was retarded; first, by the improper application of motors. Attempts were made to utilize any motor for industrial purposes provided it had the proper characteristics for the electrical power supply. Tests were not made to determine the amount and duration of the load. Often the motor was applied without the designing engineers having any knowledge of the conditions under which the motor was to operate.

Second, the commercial controllers available were unsuitable for the service and few engineers were making a specialty of this design. The few controller engineers were not associated with the men designing the motors so that there was no mutual adjusting of the apparatus to suit industrial conditions, although at that time the railway field was well developed.

Third, central station managers were making little effort to advise their customers what applications were advisable and assisting them to get satisfactory results.

About five years ago systematic efforts were begun to investigate this field. Where motor drives were not satisfactory, tests were made to determine the actual characteristics of the load. The conditions surrounding the motor were noted; the method of connecting the motor to the load was studied. Experiments were made to develop the best method for controlling the motor for each individual application. This led manufacturers to bring out special motors having the proper electrical and mechanical features to suit particular applications, and capable of satisfactory control.

The controller problem, however, shows the most marked development. The hand-operated controllers have been simplified and made more serviceable. A rapidly increasing line of automatic controllers has been placed on the market. We have developed electrical devices to replace the human brain in the operation of motors. The motor has been made to execute a complicated cycle of operation by means of a small master switch or push button. These controllers, although seemingly complicated are remarkably substantial and easily kept in repair.

There are few drives to which an electric motor cannot be applied profitably if the application is made by a competent engineer. Unfortunately, the number of engineers competent to develop new applications of electric motors is limited. This condition of affairs is largely due to the fact that many engineers do not realize the importance of investigating these applications. A few of the large industries have developed a corps of electrical engineers who have given their whole attention to motor applications. These industries have made rapid strides in electrical development, but unfortunately for the central station, these large corporations have their own power plants.

To make the greatest profit on their investment the central stations must investigate motor applications, either by using the experts trained by large motor manufacturers or else by developing their own corps of experts.

Two articles in the February 1910 issue of the *Electric Journal* give instances of each of the above cases. Consulting engineers would do well to retain controller experts capable of devising special apparatus when necessary, or applying standard controllers to special cases with more intelligence than is often displayed. The many cases of dissatisfaction with motors and controllers which have come to the writer's attention during the last few years, have generally been due to lack of exact information at the time the apparatus was ordered. It is impossible to extend the use of motor drive unless the customer is satisfied. No matter who is to blame for the trouble, the central station is the loser. The elaboration of central station practice and advantages is of no avail unless we have a market for the power, and motor driving is considered by all as a very desirable element of the load.

Begin with the machine the motor drives and work back to the central station. Furnish the customer with power in the form best suited to his uses. If his machinery requires direct current motors, transform your power to direct current; perhaps a synchronous motor will improve your line characteristics. Do not try to "ram an induction motor down his throat" to save your investment in converting apparatus. A failure at one place may prejudice the local trade against the induction motor and prevent its use at another place where it is the best motor for the service. It is not enough to furnish a motor that will turn over. We must use a motor that can be successfully controlled and then see that the customer has the proper control and is instructed how to use it.

C. A. Graves (by letter): Mr. Main states that the chief items of cost in textile mills are material and labor. Such mills, therefore, should locate in or near cities where cheap labor can be obtained instead of locations where cheap power can be obtained. Also the mill owners should welcome every improvement which will give steady uniform power, as this means increased output without increased labor cost.

It has been demonstrated in numerous instances that central station service, because of its more uniform voltage and frequency, has increased the output in various industries. Therefore owners should be willing to pay for the power which enables them to obtain this increased output. Central stations, because of their reserve equipment and duplicate distribution line, can guarantee continuous service, as is done by the Brooklyn and New York companies in their contract with New York City.

Mr. Hale expresses the situation very well when he says that central stations have no cheap unreliable power for sale.

Regarding the question of load factor, textile mills, I am informed, do not run ten hours per day, every working day in the year, but are shut down about two weeks for inventory and repairs and often Saturday afternoons in the summer time. Another point; curve drawing wattmeters which have been installed on the switchboards of various industries show that the hands do not start working until 7:30 and that the best work, or the most power taken is between 10 o'clock and 11 o'clock. After that time, the load gradually falls off until noon. The same thing happens in the afternoon, except that the load seldom goes as high as in the morning. These facts, then, when taken into account, bring the load factor of the mill below that of large central stations.

The basis of figuring cost of power at $33, per kw-hr. of capacity of plant is not an accurate method, as most plants have a capacity larger than their average load, and some few will run overload part of the time. The proper basis is the maximum load.

Let me give an illustration. One of the recent customers of the Brooklyn Edison Company with a 500-h.p. installation, who was selling power to one of his tenants for $50 per h.p-yr., taking the rated horse power of the motors as a basis, found upon installing a wattmeter, that he was receiving 1¼ cents per kw-hr., for the current, besides furnishing motors. Another extreme case which came to my notice was that of a man selling power at $60 per h.p-yr. for a 10-h.p. motor when the wattmeter showed he was charging at the rate of 20 cents per kw-hr. If these tenants had been charged on the basis of their maximum demand and the current consumption, the charges would have been more just. With the accurate measuring instruments used in the sale of electric current, the old terms employed have to be more accurately defined.

J. H. Gardiner (by letter): Mr. Stickney's paper is evidently intended to be but a brief review of the question of industrial lighting and to touch only the salient points of a very comprehensive subject. It contains much excellent information admirably condensed. The recommendation of general, as opposed to strictly local illumination, is undoubtedly correct from both a physiological and a practical standpoint, and accords with the best modern practice.

In the paragraph treating of lamps, however, it seems as though a brief statement in reference to the Nernst glower lamp might well have been made in view of the peculiar adaptability of this type of lamp to industrial lighting. The features which commend it particularly for this work are its ruggedness, the natural downward distribution of the unit, thus obviating the necessity of reflecting glassware which is always troublesome in an industrial establishment; and most important of all, the low maintenance cost. Maintenance cost becomes the preponderating factor in the total, where the cost of electrical energy is as low as in the case of large industrial installations, and is often the determining one when the choice of high efficiency systems is considered.

H. D. Jackson (by letter): Mr. Hales' paper was entirely from the central station man's point of view, and does not take into consideration the conditions governing power cost in most industrial plants. In the first place, there is no inherent reason why an industrial power plant of fair size should not produce power approximately as cheap as the central station even of large size. The power plant of an industrial establishment can, if necessary, be built with all of the refinements used in the central station, and the operating cost of the plant made very low, nearly as low as the central station, the only difference being the slight gain in economy of large units over moderate sized units, so that as far as operating expenses go, there is no reason why the smaller plant should suffer materially in comparison with the larger.

As a rule, the fixed charges against the industrial plant would not be greater than against the central plant, as the industrial plant would not be duplicated, whereas the central station plant would have to use extra apparatus in order to preserve continuity of service. This being the case, the cost of power including all charges, fixed and operating, of the two plants situated in the same locality and under the same conditions, would not vary materially.

The above is based on both plants being operated under the same conditions as regards load factor. It is a fact, however, that the central station load factor is very much lower than that of the industrial plant, and the load of the central station far more fluctuating. It is well recognized that a low power factor or a fluctuating load increases to a considerable extent the power cost. This being the case, the difference in the power cost between the two stations would be materially diminished. In some cases this may be to a certain extent offset by the shutting-down period of the industrial plant. This, however, would not influence conditions to a very great extent, as the central station has periods of this character also, although shorter in duration and not complete shutdowns.

The industrial plant is not as a rule as well located for producing power as the central station, so that an increase to the power cost must be made due to increased cost of fuel, etc., in the industrial plant's location. On the other hand, when the total cost of power at the industrial plant switchboard is figured, that is the end of the power cost when generated by the plant itself; whereas this point at the central station is only the first step. The power in this case has yet to be delivered to the customer. According to most central station men, the cost of delivering the power to the customer, metering, billing, etc., is equal to or greater than the cost of production. This being the case and the difference in cost of power slight if plants are built along the same lines as regards refinement, the central station would find it impossible to *deliver* power at the same price the plant could produce it for.

Mr. Hale speaks of the insurance factor of the central station. In order to insure continuity of service, the central station must have not only spare apparatus, but also duplicate lines for distribution—otherwise the power is no more certain than that of the industrial plant. To use an old phrase: " A chain is no stronger than its weakest link ", and the single line distributing system is in this case the weak link, which is quite as apt to fail as the high grade unit in the industrial plant, so that the insurance factor of the central station exists only in the imagination. The failure of a unit in the industrial plant affects but that plant. The failure of the central station in either line or plant may affect many plants.

In order to sell power to an industrial plant, the central station must of necessity be able to produce it at a very much reduced cost as compared to the industrial plant; and the costs of distribution, such as maintaining the distributing system, cost of metering, billing, collecting, and other charges incidental to central station service—must be reduced to a minimum and the cost of power as delivered to the customer has to include all of these items. The cost of power in an industrial plant consists of all of the items incident to the production of that power, but has absolutely nothing to do with the costs of distributing it.

So far, we have considered two plants for producing power alone, and no other use of steam has been taken into account. Most industrial plants have use for heat, either to warm the buildings or for manufacturing purposes. If exhaust steam will serve the purpose, this can readily be taken from the engine, under which condition a much less costly plant will be installed, reducing the fixed charge, also reducing the operating charge, as the steam thus used cannot be properly charged up entirely against power, as it would have to be produced in some way if the engines did not exist, nor can the boilers required for this steam be entirely charged up against power, as they would also have to exist for producing steam if power was purchased. Thus the greater the steam required for industrial purposes, the less the cost of power, not only as regards operation, but also in fixed charges.

A paper presented at a joint meeting of the American Society of Mechanical Engineers and the American Institute of Electrical Engineers, New York, March 8, 1910.

TEST OF A 15,000-KW. STEAM-ENGINE-TURBINE UNIT

BY H. G. STOTT AND R. J. S. PIGOTT

During the year 1908 it became apparent that owing to the cost of increasing traffic in the New York subway, it would be necessary to have additional power available for the winter of 1909-1910.

The power plant of the Interborough Rapid Transit Company, which supplies the subway, is located on the block bounded by 58th and 59th Streets, and by 11th and 12th Avenues, adjacent to the North River; it contains nine 7500-kw. (maximum rating) engine units, besides three 1250-kw. 60-cycle turbine units which are used exclusively for lighting and signal purposes.

The 7500-kw. units consist of Manhattan-type compound Corliss engines, having two 42-in. horizontal high-pressure cylinders and two 86-in. vertical low-pressure cylinders. Each horizontal high-pressure cylinder and vertical low-pressure cylinder has its connecting rod attached to the same crank, so that the unit becomes a four-cylinder 60-in. stroke compound engine with an overhanging crank on each side of a 7500-kw. maximum rating 11,000-volt, three-phase, 25-cycle generator. The generator revolving field is built up of riveted steel plates of sufficient weight to act as a flywheel for the two engines connected to it. This arrangement gives a very compact two-bearing unit. The valve gear on the high-pressure cylinders is of the poppet type, and on the low-pressure of the Corliss double-ported type.

The condensing apparatus consists of barometric condensers, arranged so as to be directly attached to the low-pressure exhaust nozzles, with the usual compound displacement circulating pump and simple dry-vacuum pump.

These engines and generator units are in general probably the most satisfactory large units ever built, as five years' experience with them has proved; their normal economic rating is 5000 kw., but they operate equally well (water rate excepted) on 8000 kw. continuously.

In considering the problem of how to get an additional supply of power, every available source was considered, but by a process of elimination only two distinct plans were left in the field.

The electric transmission of power from a hydraulic plant was first considered, but owing to the high cost of a double transmission line from the nearest available water power, and the impossibility of getting reliable service (that is, service having a maximum total interruption of not more than ten minutes per annum) from such a line, further consideration of this plan was abandoned.

The gas engine, while offering the highest thermo-dynamic efficiency at the same time required an investment of at least 35 per cent more than an ordinary steam-turbine plant with a probable maintenance and operation account of from four to ten times that of the steam turbine.

The reciprocating-engine unit of the same type as those already installed, was rejected in spite of its most satisfactory performance, on account of the high first cost and small range of economical operation. Reference to Fig. 1, Series A will show that the economic limits of operation are between 3300 kw. and 6300 kw.; beyond these limits the water rate rises so rapidly as to make operation undesirable under this condition, except for a short period during peak loads.

The choice was thus narrowed down to either the high-pressure steam turbine or the low-pressure steam turbine. There was sufficient space in the present building to accommodate three 7500-kw. units of the high-pressure type, or a low-pressure unit of the same size on each of the nine engines, so that the questions of real estate and building were eliminated from the problem.

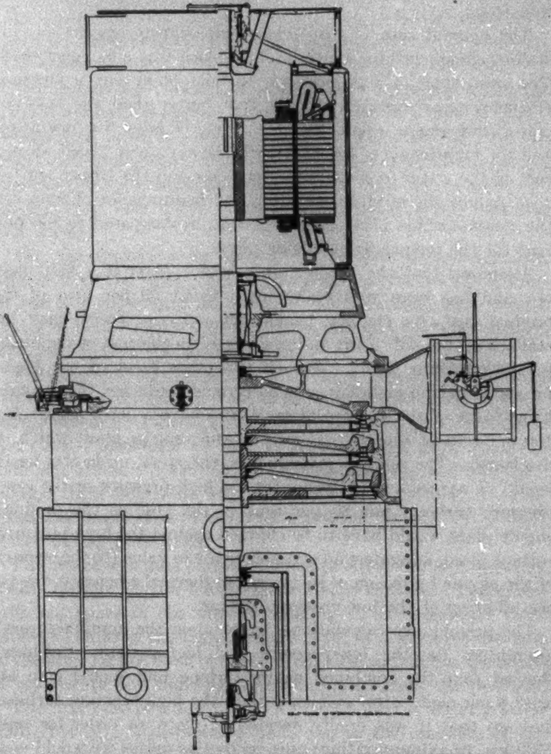
The first cost of a low-pressure turbine unit is slightly lower than that of a high-pressure unit, due to the omission of the high pressure stages and the hydraulic governing apparatus, but the cost of the condensing apparatus would be the same in both cases. The foundations and the steam piping in both cases would not differ greatly. The economic results, so far as the first cost is concerned, would then be approximately the same, if we consider the general case only; but in this particular instance the installation of high-pressure turbines would have meant a much greater investment for foundations, flooring, switchboard apparatus, steam piping and water tunnels, amounting to an addition of not less than twenty-five per cent to the first cost.

The general case of displacing reciprocating engines and installing steam-turbine units in their place was also considered. The best type of high-pressure turbine plant has a thermal efficiency approximately 10 per cent better than the best reciprocating-engine plant, but the items of labor for operation and for maintenance, together with the saving of about 85 per cent of the water for boiler-feed purposes and the 10 per cent of coal, reduce the relative operating and maintenance charges for the steam-turbine plant to 80 per cent, as compared to 100 per cent for the reciprocating-engine plant.

Assuming that the reciprocating engine plant is a first-class one and has been well maintained, about 20 per cent of its original cost (for engines, generators and condensers) may be realized on the old plant and so credited to the cost of the high-pressure turbine plant. But on the other hand, if the high-pressure turbine installation is to receive credit for the second-hand value of the engines, it must also have a debit charge for 100 per cent of the original reciprocating-engine plant which it displaced. The relative investments, therefore, upon this basis would be approximately equal for the high-pressure or the low-pressure turbine; but 80 per cent of the cost of the original engine plant would have to be charged against the high-pressure turbine plant, as against an actual increase in value (to the owner) of the engine by reason of its improved thermal efficiency, due to the addition of the low-pressure turbine.

The preliminary calculations, based upon the manufacturers' guarantees for the low-pressure and high-pressure turbines, showed that the combined engine-turbine unit would give at least 8 per cent better efficiency than the high-pressure turbine unit, so that it was finally decided to place an order for one 7500-kw. (maximum rating) unit, as by this means we would not only get an increase of 100 per cent in capacity, but at the same time give the engines a new lease of life by bringing them up to a thermal efficiency higher than that attained by any other type of steam plant.

The turbine installed is of the vertical three-stage impulse type having six fixed nozzles and six which can be operated by hand, so as to control the back pressure on the engine, or the division of load between engine and turbine. An emergency overspeed governor, which trips a 40-in. butterfly valve on the



Elevation and part section of low pressure turbine unit

steam pipe connecting the separator and the turbine and at the same time the 8-in. vacuum breaker on the condenser, is the only form of governor used. The footstep bearing, carrying the weight of the turbine and generator rotors, is of the usual design supplied with oil under a pressure of 600 lb. per sq. in. with the usual double system of supply and accumulator to regulate the pressure and speed of the oil pumps.

The condenser contains approximately 25,000 sq. ft. of cooling surface arranged in the double two-pass system of water circulation with a 30-in. centrifugal circulating pump having a maximum capacity of 30,000 gal. per min. The dry vacuum pump is of the single-stage type, 12-in. and 29-in. by 24-in., fitted with Corliss valves on the air cylinder. The whole condensing plant is capable of maintaining a vacuum within 1.1 in. of the barometer when condensing 150,000 lb. of steam per hr. when supplied with circulating water at 65 deg. fahr.

The electric generator is of the three-phase induction type, star-wound for 11,000 volts, 25 cycles and a speed of 750 rev per min. The rotor is of the squirrel-cage type with bar winding connecting into common bus-bar straps at each end. This type of generator was chosen as being specially suited to the conditions obtaining in the plant.

With nine units operating in multiple, each one capable of giving out 15,000 kw. for a short time, operating in multiple with another plant of the same size, it is evident that it is quite possible to concentrate 270,000 kw. on a short circuit. If we proceed to add to this, synchronous turbine units of 7500-kw. capacity, which, owing to their inherently better regulation and enormous stored energy, are capable of giving out at least six times their maximum rated capacity, the situation might soon become dangerous to operate, as it would be impossible to design switching apparatus which could successfully handle this amount of energy. The induction generator, on the other hand, is entirely dependent upon the synchronous apparatus for its excitation, and in case of a short circuit on the bus-bars would automatically lose its excitation by the fall in potential on the synchronous apparatus.

The absence of fields leads to the simplest possible switching apparatus, as the induction generator leads are tied in solidly through knife switches, which are never opened, to the main generator leads. The switchboard operator has no control whatever over the induction generator, and only knows it is present by the increased output on the engine generator instruments.

The method of starting is simplicity itself—the exciting current is put on the engine generator *before* starting the engine, and then the engine is started, brought up to speed and synchronized in exactly the same way as before. While starting in this way, the induction generator acts as a motor until sufficient steam passes through the engine to carry the turbine above synchronism, when it immediately becomes a generator and picks up the load. Three of these 7500-kw. low-pressure turbine units have been installed and tests run on Nos. 1 and 2. No. 3, having been just started, has not yet been tested.

Instead of inserting in this paper the enormous accumulation of data incident to these tests, we have divided the paper into two parts in the hope that it would thus be more accessible for reference, the first part giving the reasons for adopting this particular type of apparatus, with a brief description of the plant and a summary of the results obtained, and the second part containing all the principal data acquired during the tests, with sufficient explanation to make their meaning clear without reference to the text.

The tables and curve sheets are as follows:

Series A: Engine tests made in connection with acceptance tests, and also later to determine best conditions for operation.

Series B: Calculations and data furnished by turbine manufacturer to determine probable results when combined with engine data obtained in Series A.

Series C: Tests on No. 1 combined unit. This unit was hurriedly put into commission in order to obtain results to determine future developments. To get the piping done, old riveted steel pipe was used which was very leaky under vacuum. Results are valuable however as showing the effect of vacuum on performance as compared to Series E and F. Quality of steam entering turbine also poor.

Series D: Tests of No. 2 unit, with poor vacuum and poor quality of steam entering turbine.

Series E and F: Tests on No. 2 combined unit: conditions of vacuum and quality of steam entering turbine nearly standard, so that corrections are small.

In all results, except where specially noted, moisture corrections are simple corrections, *i.e.*, for each per cent of moisture only one per cent correction has been made. Vacuum corrections for the combined unit are 1 lb. for each inch variation from 28.5 in. when referred to 29.92 in. barometer.

The net results obtained by the installation of low-pressure turbine units may be summarized as follows:

a An increase of 100 per cent in maximum capacity of plant.

b An increase of 146 per cent in economic capacity of plant.

c A saving of approximately 85 per cent of the condensed steam for return of the boilers.

d An average improvement in economy of 13 per cent over the best-high pressure turbine results.

e An average improvement in economy of 25 per cent (between the limits of 7000 kw. and 15,000 kw.) over the results obtained by the engine units alone.

f An average unit thermal efficiency between the limits of 6500 kw. and 15,500 kw. of 20.6 per cent.

TABLE 1 SERIES A, ENGINE TESTS

No. of test	Eng. load kw.	Steam pressure lb. gauge	Steam temperature deg. fahr.	Steam superheat deg. fahr.	Receiver pressure (from temp.) lb. gauge	Vacuum std. in. 29.92 in mercury	Quality of steam per cent	Water per hr. lb.	Dry steam per hr. lb.	Rec. drain per hr. lb.	Steam to auxiliary lb.	Inject water temp. deg. fahr.	Disch. water temp. deg. fahr.	i.h.p. high-pressure h.p.	i.h.p. low pressure h.p.	i.h.p. total h.p.	Dry steam per kw-hr. lb.	Dry steam per i.h.p. hr. lb.
25	3100	180.1	388.3	9.7	9.13	28.81	100.55	56040	56349	2989	1517	36.8	55.7	2173	2306	4479	18.18	12.58
22	4008	176.7	383.9	5.7	16.87	27.99	100.32	68190	68407	4882	1866	38.4	58.3	2699	2815	5514	17.07	12.42
24	4977	174.4	387.8	10.6	21.7	28.00	100.58	85369	85865	5273	2949	36.8	65.3	3264	4076	7341	17.25	11.70
21	5984	173.9	387.5	10.5	25.9	28.00	100.60	103896	104519	6031	1699	37.73	69.5	3717	4714	8431	17.47	12.40
23	6772	173.3	385.5	8.7	30.0	27.71	100.50	124702	125326	6060	2091	37.7	70.4	4346	5732	10078	18.51	12.37
27	4992	173.9	387.3	10.5	10.44	28.11	100.60	89525	99062	5367	1826	37.76	72.66	3770	5184	6954	18.04	12.95
26	4970	173.2	386.1	9.4	15.21	28.00	100.53	86267	86724	5518	1728	35.9	61.1	3443	3452	6895	17.45	12.58
29	4976	174.9	386.9	9.4	20.41	28.00	100.53	85557	86010	5294	3034	38.1	75.0	3124	3722	6846	17.29	12.59
28	4970	174.3	388.8	11.7	25.35	28.02	100.66	85933	86501	4890	663	36.7	72.6	2982	4127	7109	17.42	12.17
31	3988	177.7	387.5	8.9	32.63	—	100.51	109317	109874	5948	—	—	—	2625	2372	4997	27.55	21.99
32	4980	176.2	386.7	8.7	36.93	—	100.50	128056	128695	6352	—	—	—	2835	3333	6168	25.84	20.88
30	4961	148.2	372–0	7 0	21.06	28.01	100–40	88041	88394	5082	1284	37.46	72.4	3068	4019	7087	17.82	12.48

TABLE 2—SERIES A

No. of test	Eng load kw.	B.t.u. added per pound water	B.t.u. rej. per pound water	Eff. Rankine per cent	Eff. thermal per cent	$\frac{\text{Eff}_T}{\text{Eff}_R}$ per cent	B.t.u. drains per cent	B.t.u. con's'r and rad'n loss per cent	B.t.u. mech. elec. loss per cent	Remarks
25	3100	1205	840	30.3	15.7	51.7	0.9	71.4	12.0	
22	4008	1202	865	28.0	16.7	59.6	1.3	70.0	"	
24	4977	1204	866	28.1	16.5	58.1	1.2	70.3	"	
21	5984	1204	866	27.1	16.3	58.2	1.1	70.6	"	
23	6772	1203	875	28.3	15.4	56.4	1.0	71.6	"	
27	4992	1205	865	28.2	15.8	56.0	1.0	71.2	"	
26	4970	1204	866	28.1	16.3	58.1	1.2	70.5	"	
29	4976	1205	866	28.1	16.4	58.6	1.2	70.4	"	
28	4970	1206	866	28.2	16.4	58.1	1.1	70.5	"	
31	3988	1205	1017	15.6	10.3	66.2	1.1	76.6	"	Non-condensing
32	4980	1204	1017	15.5	11.0	71.1	1.0	76.0	"	Non-condensing
30	4961	1200	875	27.1	16.0	59.7	1.1	70.9	"	

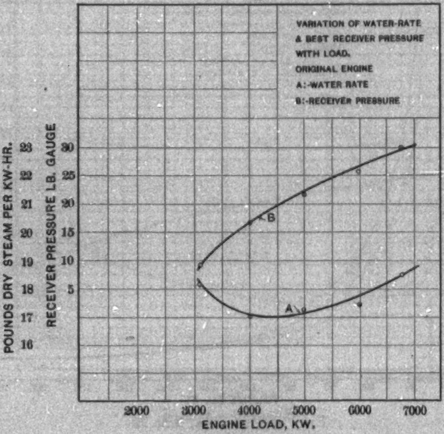


Fig. 1.—Series A

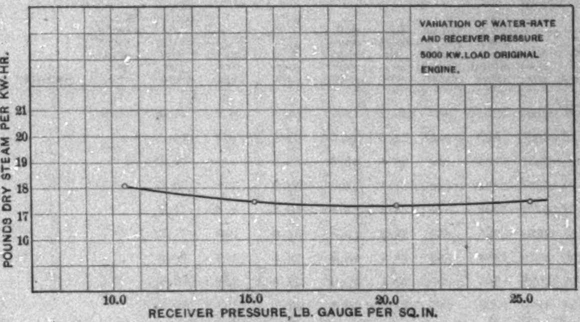


FIG. 2.—Series A

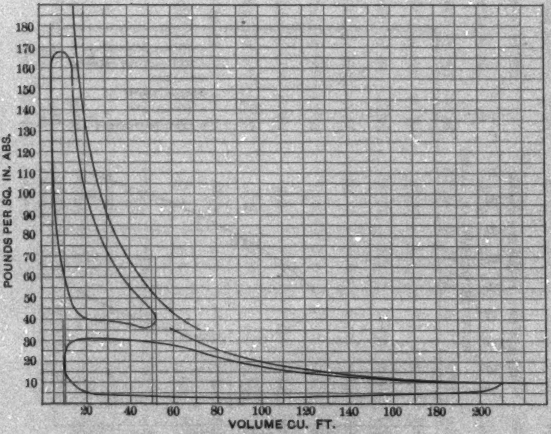


FIG. 3.—Series A, test 29

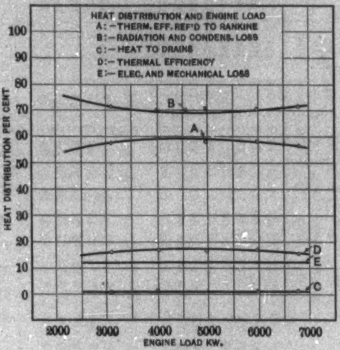


FIG. 3*a*.—Series A

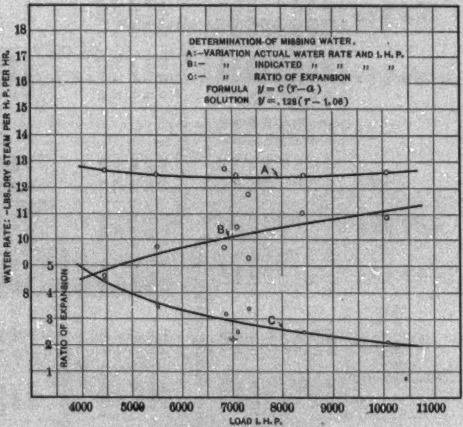


FIG. 4.—Series B

TABLE 3 SERIES B

No. test	Load kw.	i.h.p.	Ratio high press. / low press. i.h.p.	P_a lb. per sq. in. abs.	P_c lb. per sq. in. abs.	V_a cu. ft.	V_c cu. ft.	W_a lb. per cu. ft.	W_c lb. per cu. ft.	Steam per stroke high press. card lb.	r	y	Indic. water rate per i.h.p. lb. per hr.	Actual water rate per i.h.p. lb. per hr.	Actual water rate per kw-hr. lb. per hr.	Receiver press. per lb. sq. in. abs.	Exhaust press. lb. per sq. in. abs.	Steam press. lb. per sq. in. abs.	Steam press. total water lb. per hr.
25	3100	4479	0.943	137.32	66.12	10.78	7.56	0.3058	0.1544	2.131	4.80	0.469	8.57	12.59	18.18	19.8	0.9	191.5	56349
22	4008	5515	0.959	143.0	65.3	13.77	9.31	0.3176	0.1526	2.951	3.41	0.298	9.64	12.41	17.07	31.6	1.0	192.8	68407
29	4976	6846	0.840	142.4	73.8	16.64	9.30	0.3163	0.1709	3.670	3.11	0.302	9.65	12.56	17.29	36.4	1.0	190.9	86010
24	4977	7341	0.801	141.8	75.7	17.13	9.30	0.3151	0.1751	3.769	3.32	0.265	9.24	11.69	17.25	35.1	0.9	191.0	85865
21	5984	8431	0.789	141.8	74.1	21.48	9.29	0.3142	0.1716	5.154	2.42	0.128	11.00	12.40	17.47	40.6	0.9	191.0	104519
23	6772	10078	0.759	140.6	89.0	25.40	9.29	0.3126	0.2037	6.080	2.04	0.154	10.86	12.44	18.51	44.7	1.0	190.9	125326
31	3988	5900	1.403	143.7	72.2	19.83	7.56	0.3191	0.1675	5.058	3.11	0.206	15.43	18.62	27.55	47.3	14.7	192.2	109874
32	4981	7004	0.807	143.7	75.8	23.44	7.57	0.3191	0.1753	6.154	2.21	0.155	15.81	18.28	25.84	51.6	14.7	189.7	128695
Assumed cards, variable nozzle pressure																			
A	4050	5936	1.04	187.8	82.5	10.93	4.70	0.4107	0.1897	3.597	4.73	0.474	12.00	17.69	25.92	39.7	7.0	215	105000
B	5590	8192	1.05	182.2	96.0	16.45	"	0.3991	0.2186	5.537	3.14	0.268	12.18	15.45	22.63	46.0	10.0	"	126600
C	6710	9836	1.07	176.0	119.5	22.80	"	0.3862	0.2685	7.55	2.27	0.156	13.62	15.98	23.40	52.2	13.5	"	157300
D	7370	10792	1.10	168.6	122.8	29.83	"	0.3708	0.2753	9.71	1.73	0.087	16.30	17.72	25.95	58.5	18.0	"	191100
E	7740	11336	1.05	160.9	136.2	37.60	"	0.3549	0.3034	11.92	1.31	0.033	18.91	19.54	28.61	64.7	23.0	"	221400
Assumed cards, constant nozzle pressure																			
F	3875	5676	1.12	182.2	136.2	16.45	"	0.3991	0.3034	5.140	3.14	0.268	16.31	20.69	30.30	64.7	16.0	"	117400
G	5795	8484	0.988	176.0	"	22.80	"	0.3862	"	7.374	2.27	0.156	15.57	18.00	26.38	"	"	"	152700
H	7190	10540	0.974	168.6	"	29.83	"	0.3708	"	9.633	1.73	0.087	16.45	17.88	26.20	"	"	"	188500
I	8200	12008	0.938	160.9	"	37.60	"	0.3549	"	11.92	1.31	0.033	17.86	18.45	27.04	"	"	"	221700

TABLE 4—SERIES B

Assumed cards low pressure exhaust quality data											
No.	Water p. hr. lbs.	High press. steam to low press cylinders per cent	Moisture at low press. admission per cent	Admission press. lb. per sq. in. abs.	Relief press. lb. per sq. in. abs.	Exhaust press. lb. per sq. in. abs.	r	Quality of low press. exhaust per cent	Comb. quality per cent	Dry steam turb. lbs. per hr.	
A	105000	93.2	2.5	37	9.5		2.76	90.6	84.4	88600	Variable nozzle press.
B	126600	94.3	3.0	43	14		2.47	90.9	85.7	108500	
C	157300	95.2	3.5	49	19		2.26	91.4	86.9	136700	
D	191100	95.9	4.0	55	24		2.10	91.6	87.8	167800	
E	221400	96.2	4.0	60	28		1.98	91.9	88.4	195600	
F	117400	96.8	3.0	60	20	17.5	3.30	90.8	84.5	99200	Constant nozzle press.
G	152700	95.7	3.5	"	20	"	2.94	90.5	85.5	130600	
H	188500	94.4	4.0	"	23	"	2.46	90.8	86.9	163800	
I	221700	93.1	4.0	"	27	"	1.98	91.6	88.7	196600	

REMARKS AND FORMULAE

Tests 21–29 inclusive, 8 hr.

Tests 31–32, 8 hr. atmospheric exhaust non-condensing.

$$\frac{\text{i.h.p.}}{\text{kw.}} = 1.465$$

$r = \dfrac{51.7}{V_a}$ for high-press. card = ratio of expansion.

$y = 0.129\ (r - 1.06)$ = missing water.

w = Sp. density at p.

$$W_a \times V_a = W_1 \qquad W_c \times V_c = W_2 \qquad W_1 - W_2 = W_3$$

$$\frac{W_3 \times 60 \times 4 \times 75}{\text{i.h.p.}} = \text{i. w. r. at high press. cut-off.}$$

I. w. r. $\times (1+y)$ = a. w. r. per i.h.p. hr.

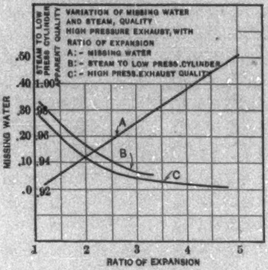


FIG. 5.—Series B

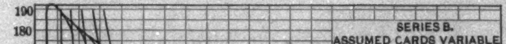


FIG. 6.—Series B

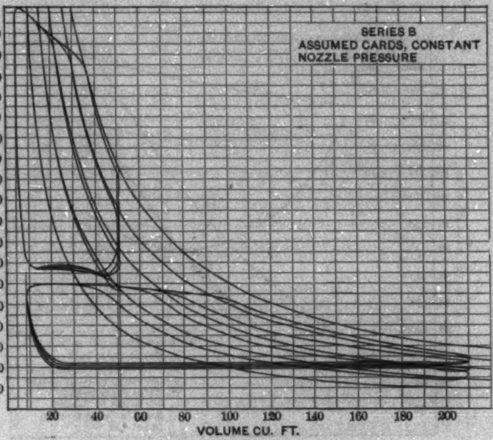


FIG. 7.—Series B

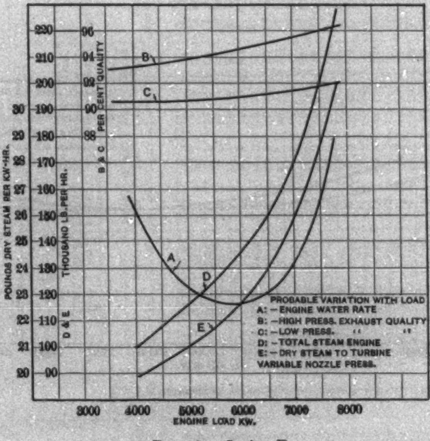


FIG. 8.—Series B

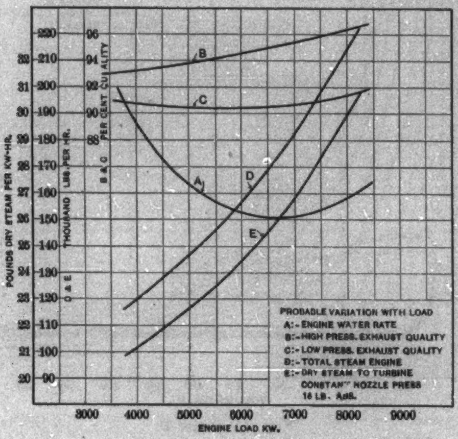


FIG. 9.—Series B

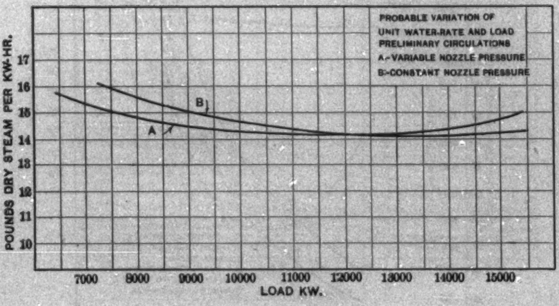


FIG. 10.—Series B

TABLE 5 SERIES C

Resume of observations — Corrected to 29.92 in. barometer and 14.7 lb. atmos.

		Loads			Pressures					Qualities		Water			Dry steam		Temperatures		
	Duration	Unit	Engine	Turbine	High press. steam	Receivers	Low press. steam	Low press. steam	Vacuum	High pressure steam	Low pressure turb.	Separator low pressure	Turbine discharge	Total unit	Turbine	Eng. and unit	Hot well cond.	Injection	Disch. circ. water
Test No.	hours	kw.	kw.	kw.	lb. gauge per sq. in.	lb. gauge per sq. in.	lb. abs. per sq. in.	lb. gauge per sq. in.	in mercury	Per cent	Per cent	lb. per hour	lb. per hour	lb. per hour	lb. per hour	lb. per hour	deg. fahr.	deg. fahr.	deg. fahr.
5	4	10220	6627	3690	174.4	36.2	12.72	—	28.03	97.08	90.89	3369	150170	153540	136500	149000	88.1	72.1	84.0
6	5	11320	6520	4870	173.4	35.7	17.22	1.52	28.34	96.96	94.09	2759	167190	169950	158200	164850	87.6	74.7	87.8
7	3	11150	6187	4960	173.4	33.9	17.36	2.66	28.55	97.06	90.17	1157	164945	166100	148350	161200	85.5	72.5	86.0
8	3	10970	6178	4840	170.2	49.6	17.36	2.66	28.44	97.15	88.62	654	161612	162270	143200	157700	86.9	74.4	86.6
9	2	11250	6560	4685	170.2	50.1	16.61	1.91	28.18	97.08	92.08	5830	164458	170290	151900	165300	87.8	72.8	86.3
10	1	12440	7060	5400	172.0	49.3	17.60	2.90	27.91	97.54	86.96	3133	185100	188230	161400	183600	89.5	72.0	83.3
11	2	8990	5195	3795	172.0	50.0	16.61	1.91	27.92	97.54	91.32	469	136850	137320	124890	133930	87.3	72.4	83.5
12	1	13240	7580	5610	172.6	48.8	17.06	2.36	27.99	98.32	85.06	6018	192290	198310	163500	194900	90.7	75.4	89.2
13	2	10240	6070	4220	172.0	47.1	16.80	2.10	27.98	98.50	91.05	825	156470	157290	142470	154900	88.2	72.8	83.8
14	2	11480	6140	5340	174.8	51.4	18.84	4.14	28.29	98.41	90.24	337	176210	176550	159010	173740	86.4	73.0	86.6
15	5	11504	6022	5468	170.8	48.1	19.45	4.75	27.51	97.83	95.15	—	167103	—	159000	—	91.8	78.2	93.5
16	7	11526	6314	5203	173.9	48.4	19.45	4.75	27.42	98.02	93.57	9633	167085	176718	157300	173200	92.9	78.6	91.5
17	5	11528	6084	5488	175.7	49.5	19.90	5.20	27.62	97.70	94.68	5111	179170	184301	169650	180100	86.4	73.6	86.7
18	6	10740	5916	4831	174.1	49.5	18.56	3.86	27.65	98.19	94.83	12554	149148	161702	141450	158750	89.7	72.8	83.6
19	6	14540	7860	6692	174.0	51.7	18.42	3.72	27.78	97.66	95.07	16404	201351	217755	191450	212700	90.9	72.2	88.2
20	4	14365	7373	6962	171.6	52.2	20.94	6.24	27.75	97.88	96.47	15423	196680	212103	189750	207750	90.3	72.6	93.7
21	6	10320	5632	4617	175.9	49.8	17.77	3.07	28.03	97.54	89.52	6486	144399	150885	129150	147100	87.8	72.5	84.4
23	6	13410	7460	5862	173.9	50.2	18.01	3.31	27.72	97.80	96.09	15760	195514	211274	188000	206800	91.1	73.0	87.0
24	6	12927	7033	5820	169.8	50.2	18.59	3.89	27.79	98.03	95.47	14439	173150	187589	165300	183950	89.8	73.3	86.8
25	6	9730	5142	4508	175.3	49.7	18.99	4.29	27.78	97.77	96.46	11189	134635	145824	129840	142600	88.8	72.3	82.8
26	6	11840	6470	5305	172.6	49.2	19.02	4.32	27.48	98.18	96.48	14090	161983	176073	156300	172900	88.2	73.1	84.9
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

TABLE 6 SERIES C

Results									Guarantee and calculated water rates			Circ. water				
Test	Load	Water rates (dry steam)														
		Turbine	Engine	Unit		Unit	Unit		Turbine	Engine	Unit			Water rate		
		Actual				moist corr.	total corr.		Constant nozzle pressure			Ratio	Total	unit equivalent		
	kw.	Lb. per kw-hr.	Lb. per kw-hr.	Lb. per kw-hr.		Lb. per kw-hr.	Lb. per kw-hr.		Lb. per kw-hr.	Lb. per kw-hr.	Lb. per kw-hr.	C.W. / Dry st.	Gal. per min.	Lb. per i.h.p. hr. c.n.p.	Remarks	Formulae and notes
5	10220	36.98	22.48	14.57		14.0	13.53		28.42	26.03	14.42	89.0	26740	8.85	Varying nozzle press.	$27 = \frac{17}{4+[1+(1-12)]5}$
6	11320	32.34	25.30	14.45		14.1	13.94		27.30	26.04	14.07	80.5	26920	8.68	Auxiliary steam included c.n.p.	
7	11150	30.42	26.05	14.49		13.85	13.90		27.22	26.07	14.10	78.3	25800	9.10	Constant nozzle press.	$28 = 27-(28.5-10)$
8	10970	29.58	25.51	14.37		13.64	13.70		27.31	26.07	14.15	86.5	27960	8.76	Do	
9	11250	32.42	25.20	14.69		14.23	13.55		27.42	26.04	14.09	79.0	25980	9.03	Do.	
10	12440	29.89	26.01	14.76		13.95	13.36		27.00	26.08	13.88	93.5	30560	8.27	V.n.p.	
11	8990	32.91	25.79	14.89		14.36	13.78		28.29	26.99	15.10	94.5	25820	8.76	C.n.p.	
12	13240	29.15	25.71	14.72		13.90	13.39		26.90	26.46	13.90	76.5	30320	8.25	Do.	
13	10240	33.76	25.52	15.13		14.51	13.99		27.83	26.10	14.41	96.0	30200	9.01	Do.	
14	11480	29.78	28.30	15.15		14.47	14.26		27.02	26.10	14.03	78.6	25000	9.14	V.n.p.	
15	11504	29.06	—	—		—	—		26.97	26.24	14.01	69.0	23060	—	Aux. included c.n.p.	
16	11526	30.22	27.42	15.02		14.64	13.56		27.10	26.12	14.01	82.0	27400	8.93	C.n.p.	
17	11528	30.90	29.70	15.68		15.20	14.32		26.96	26.20	14.01	81.0	29020	9.53	Aux. included v.n.p.	
18	10740	29.26	26.84	14.78		14.41	13.56		27.31	26.30	14.22	98.0	29230	9.06	C.n.p.	
19	14540	28.60	27.05	14.62		14.30	13.58		26.63	26.69	13.80	66.0	26560	9.08	Do.	
20	14365	27.23	28.15	14.45		14.25	13.50		26.60	26.31	13.80	51.0	20050	9.05	V.n.p.	
21	10320	27.97	26.11	14.25		13.70	13.23		27.49	26.50	14.39	85.0	24520	8.52	C.n.p.	
23	13410	32.05	27.70	15.41		15.25	14.47		26.81	26.37	13.80	75.5	29520	9.81	Do.	
24	12927	28.40	26.14	14.22		14.0	14.29		26.82	26.16	13.81	78.5	27180	8.93	Do.	
25	9730	28.81	27.73	14.65		14.53	13.81		27.57	27.07	14.67	101.0	27200	9.33	Do.	
26	11840	29.45	26.71	14.60		14.44	13.42		27.04	26.09	13.96	91.0	24500	9.06	Do.	
21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**

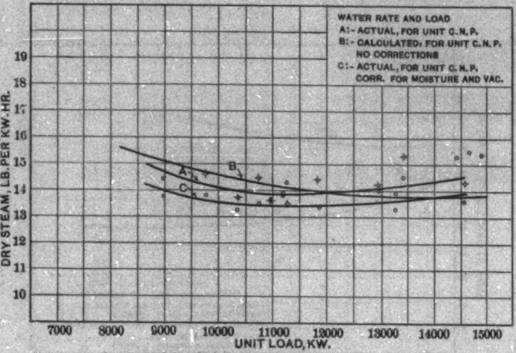


FIG. 11.—Series C

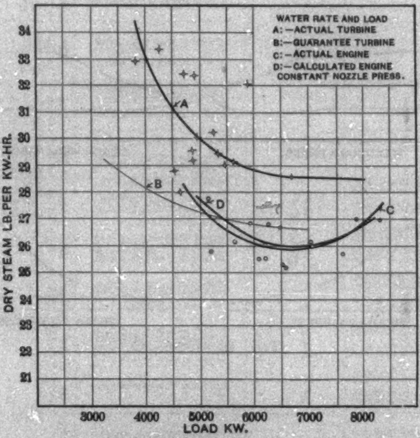


FIG. 11a.—Series C

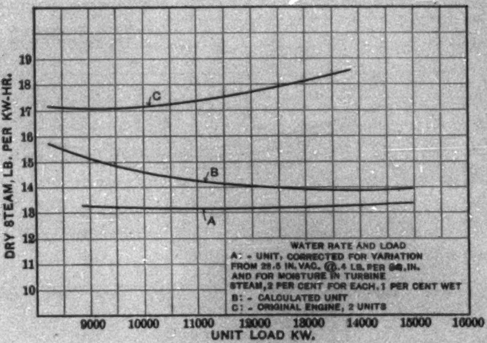


FIG. 11*b*.—Series C

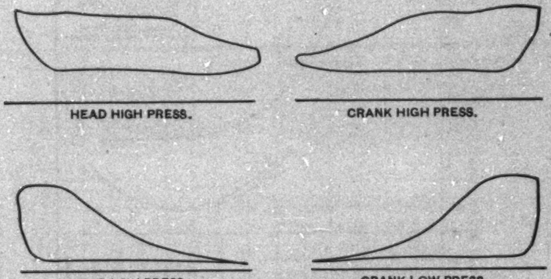

HEAD HIGH PRESS.
CRANK HIGH PRESS.
HEAD LOW PRESS.
CRANK LOW PRESS.

FIG. 12.—Series C

TABLE 7 SERIES D

Test	Duration hr.	Loads			Pressures					Qualities		Water lb. per hr.			Dry steam		Temperatures		
		Unit kw.	Eng. kw.	Turb. kw.	High press. steam lb. per sq. in. abs.	Receivers lb. per sq. in. abs.	Turb. steam lb. per sq. in. abs.	Vacuum lb. per sq. in. abs.	Vacuum 29.92 in mercury	High press. steam per cent	Turb. steam per cent	Total condensation	Turb. water	Total water unit	Turbine	Eng. and unit	Cond. hot well deg. fahr.	Circ. water injection deg. fahr.	Circ. water discharge deg. fahr.
27	6	9567	4875	4683	185.1	64.7	18.14	0.70	28.50	99.0	93.4	8636	133840	142476	125000	141100	78.6	38.80	58.60
28	6	10527	5819	4714	189.8	64.9	16.93	0.87	28.15	99.6	95.2	8570	146730	155300	139700	154700	80.4	39.53	67.04
29	2	11400	6410	5000	184.7	65.2	17.62	1.05	27.87	98.9	97.3	9601	162475	172076	158100	170300	81.3	37.40	67.77
30	4	11365	6590	4810	185.6	64.9	17.62	1.15	27.58	99.0	97.8	10088	161351	171439	157800	169700	84.5	39.20	73.90
31	6	12300	6930	5373	192.0	65.5	17.59	0.90	28.12	99.3	97.8	11006	166826	177832	163200	176800	78.64	36.54	66.00
32	6	13160	7490	5717	193.4	66.3	17.66	0.95	27.98	99.5	97.2	12142	179776	191918	174700	191000	75.34	35.70	69.72
33	4	16085	8505	7670	192.3	65.2	20.00	1.12	27.64	99.8	94.7	7312	247090	254402	234000	254000	86.44	35.05	73.41
34	6	14223	8183	6060	192.3	65.8	17.56	1.11	27.66	99.4	95.7	9361	206261	215622	197500	214300	89.06	34.88	74.30
35	4	13295	7783	5524	194.7	65.8	1713	1.20	27.49	99.5	95.4	11145	187214	198359	178600	197500	90.85	35.22	76.39
36	5	12217	7169	5033	192.7	64.3	16.28	1.05	27.78	99.8	93.8	13017	165908	178925	155500	178700	89.42	34.66	70.76
37	6	10043	5813	4184	190.4	63.9	16.40	1.02	27.84	99.4	93.7	9823	140932	150755	132000	149800	91.80	36.67	70.72

Test	Actual water-rates			Corrected Unit		I.h.p. engine			factor i.h.p.
	Eng.	Turb.	Unit	Moisture	Moist. and vac.	High press.	Low press.	Total	kw.
27	28.94	27.65	14.75	14.30	14.30	3861	3502	7363	1.511
28	26.69	30.15	14.68	14.37	14.02	4138	4359	8497	1.461
29	26.57	31.62	14.94	14.74	14.11	4445	4712	9157	1.429
30	25.74	32.81	14.93	14.74	13.82	4477	4727	9204	1.397
31	25.49	30.38	14.36	14.22	13.74	4753	5045	9798	1.414
32	25.50	30.57	14.51	14.29	13.77	5092	5583	10675	1.425
33	29.86	30.50	15.79	15.32	13.46	5902	6229	12131	1.426
34	26.18	32.60	15.07	14.78	13.94	5585	6018	11603	1.417
35	25.38	32.34	14.85	14.56	13.55	5246	5682	10928	1.404
36	24.92	30.91	14.62	14.29	13.57	4873	5421	10294	1.435
37	25.77	31.54	14.93	14.60	13.94	4248	4312	8560	1.473

TABLE 8 SERIES E AND F

No. test	Date 1910	Duration	Loads			Pressures													
			Total unit kw.	Engine kw.	Turbine kw.	Main steam abs. lb. per sq. in.	Main steam gauge lb. per sq. in.	Receivers abs. lb. per sq. in.	Receivers gauge lb. per sq. in.	Low pres. separator abs. lb. per sq. in.	Low pres. sep. gauge lb. per sq. in.	Low pres. sep. U-tube in. mercury	Vacuum Hg Col. in. mercury	Vacuum manom. in mercury abs.	Vacuum abs. lb. abs.	Barometer in. mercury	Std. vac. 29.92 Bar. in. mercury	Circ. water pump Suction in. mercury	Circ. water pump Discharge gauge lb. per sq. in.
38	Jan. 11	5	16172	8384	7784	197.0	182.3	64.2	49.5	20.60	5.90	10.94	29.30	1.50	0.74	30.63	28.42	12.7	12.0
39	11	5	13485	7798	5895	203.8	189.1	64.5	49.8	16.50	1.80	2.61	29.10	1.58	0.78	30.59	28.34	12.2	12.9
40	12	5	13038	7314	5711	196.1	181.4	63.8	49.1	16.20	1.50	1.82	29.46	1.22	0.60	30.61	28.72	11.0	12.8
41	12	5	12284	6938	5348	200.2	185.5	64.5	49.8	16.10	1.40	2.18	29.32	1.31	0.64	30.57	28.69	12.6	12.1
42	13	5	11252	6248	4938	197.0	182.3	64.0	49.3	16.24	1.54	2.20	29.41	1.32	0.65	30.65	28.60	9.9	14.3
43	13	5	10476	5824	4602	198.0	183.3	63.8	49.1	16.20	1.50	2.00	29.23	1.46	0.72	30.58	28.46	12.6	12.8
44	14	5	9408	4940	4426	198.8	184.1	63.8	49.1	16.10	1.40	2.28	29.47	0.93	0.46	30.31	28.99	9.5	11.6
45	14	1¼	9712	5916	3709	198.2	183.5	64.3	49.6	10.50		−7.48	28.96	1.22	0.60	30.21	28.70	11.6	11.6
46	15	½	12700	7180	5640	198.5	183.8	62.6	47.9	12.96		−2.78	29.45	1.03	0.51	30.32	28.89	13.75	9.5
47	15	½	11940	7060	4780	195.3	180.6	62.6	47.9	12.35		−1.80	29.72	1.03	0.51	30.32	28.89	12.9	9.9
48	15	3	9306	5865	3323	196.3	181.5	63.8	49.1	9.65		−10.49	29.13	1.20	0.59	30.33	28.72	12.0	10.6
								46.3	31.6										
49	15	1	10940	6640	4300	194.9	180.2	49.3	35.6	11.65		−6.62	29.19	1.13	0.56	30.32	28.79	12.1	10.9
50	15	4	15498	8169	7260	192.0	177.3	59.0	44.3	17.80	3.10	3.54	29.23	1.13	0.56	30.32	28.79	14.6	10.4
51	17	3	11240	6753	4376	194.0	179.3	55.0	40.3	11.50		−6.71	29.25	1.19	0.58	30.38	28.73	11.5	9.9
52	17	3	7200	4743	2400	196.5	181.8	41.5	26.8	7.97		−14.92	29.07	1.29	0.63	30.29	28.63	10.6	10.7
53	17	3	11927	7070	4834	199.0	184.3	52.9	38.2	12.75		4.58	29.10	1.25	0.61	30.26	28.67	13.2	10.1
54	26	3	14173	7820	6283	193.4	178.6	55.7	40.9	15.18	0.48	1.04	29.31	0.93	0.46	30.03	28.99	10.1	9.5
55	26	3	8347	5403	2910	197.4	182.7	43.0	28.3	8.21		−13.48	28.90	1.15	0.57	29.97	28.77	12.4	9.0
56	26	3	13033	7457	5550	197.2	182.5	54.3	39.6	14.09		−1.75	29.01	1.01	0.50	29.90	28.91	13.2	9.4
57	27	3	14580	7960	6583	199.7	179.2	59.6	45.1	15.57	0.87	+3.04	28.85	0.85	0.42	29.49	29.07	10.3	8.8
58	27	3	6673	4420	2213	197.7	183.2	40.1	25.6	7.08		−15.14	28.48	0.98	0.48	29.48	28.94	12.6	8.6
59	27	3	10007	6194	3804	199.1	184.6	47.3	32.0	10.35		−8.59	28.55	0.94	0.46	29.50	28.98	14.3	8.7
60	28	3	11820	6923	4860	195.1	180.5	51.6	36.9	12.10		−4.98	28.96	0.87	0.43	29.79	29.05	10.7	10.4
61	28	3	11480	6587	4893	196.8	182.2	51.4	36.7	12.34		−4.46	28.88	1.00	0.49	29.79	28.92	12.4	10.2
62	28	3	15860	8440	7410	195.0	180.4	63.4	48.8	17.84	3.14	7.60	28.73	1.19	0.58	29.79	28.73	13.9	9.9

TABLE 9 SERIES E AND F

		High press throttling calorimeter				No. 1 separating			No. 2 separating			No. 1 throttling				No. 2 throttling		
No. test	Load kw.	Av. main steam temp. deg. fahr.	Cal. discharge temp. deg. fahr.	Cal. discharge press gauge in. mercury	Quality per cent	Moisture lb.	Flow lb.	Quality per cent	Moisture lb.	Flow lb.	Quality per cent	Steam temperature deg. fahr.	Discharge temperature deg. fahr.	Discharge press vacuum in. mercury	Quality per cent	Discharge temperature deg. fahr.	Discharge press vacuum in. mercury	Quality per cent
38	16172	380.6	312.1	18.27	99.5	11.55	153.43	92.9				229.2	198.4	17.76	99.2			
39	13485	383.4	282.0	25.68	97.9	10.49	117.59	91.8				217.6	184.2	20.31	98.8			
40	13038	380.2	302.9	21.81	99.2	10.10	119.41	92.2				216.7	182.0	20.74	98.8			
41	12284	381.9	297.5	19.80	98.9	9.88	119.93	92.4				216.3	180.3	20.55	98.7			
42	11252	380.6	294.8	20.77	98.7	9.73	120.16	92.6	1.42	18.77	93.0	216.7	181.5	20.60	98.7	164.0	26.12	98.1
43	10476	381.0	291.8	20.42	98.5	8.86	111.94	92.6	3.18	46.47	93.6	216.7	182.9	21.50	98.8	168.9	26.23	98.4
44	9408	381.3	297.9	21.78	98.7	8.05	99.50	92.5	1.08	18.90	94.6	216.4	179.3	21.55	98.6	177.0	25.71	98.5
45	9712	381.1	294.8	21.92	98.7	1.10	14.10	92.8	0.79	11.95	93.8	195.4	172.5	23.70	99.2	159.5	27.37	98.6
46	12700	381.2	296.7	21.40	98.8	0.43	10.60	96.1	0.16	4.00	96.2	210.2	170.3	21.30	98.4	163.9	26.40	98.3
47	11940	379.9	304.0	20.63	99.1	0.29	9.10	96.9	0.16	3.60	95.8	203.3	176.0	22.48	98.9	165.7	26.72	98.6
48	9306	380.3	290.5	21.18	98.6	2.43	42.25	94.6	1.22	16.88	93.3	191.8	171.2	24.29	99.3	156.9	27.42	98.6
49	10940	373.7	299.0	21.05	98.9	0.74	16.77	95.7	0.41	6.90	94.4	200.3	178.3	22.62	99.3	167.3	26.76	98.7
50	15498	378.5	305.6	19.77	99.4	2.84	70.70	96.2	1.27	41.56	97.0	221.4	189.4	19.89	98.8	182.9	25.40	98.6
51	11240	379.4	292.6	21.93	98.6	2.04	51.67	96.2	1.15	19.96	94.5	199.8	174.8	22.68	99.0	165.0	27.04	99.1
52	7200	380.4	228.8	20.71	98.4	2.04	36.77	94.7	0.93	14.05	93.7	182.4	163.0	25.21	99.3	148.0	27.75	98.6
53	11927	381.4	294.4	20.64	98.6	1.79	56.20	95.3	1.11	21.66	95.1	204.7	177.0	21.96	99.0	168.8	26.73	98.7
54	14173	379.1	296.9	22.41	98.9	2.13	56.70	96.3				213.3	191.4	19.92	99.4			
55	8347	380.8	292.9	20.87	98.6	1.57	38.91	96.1				184.2	165.2	24.20	99.3			
56	13033	380.7	298.2	20.25	98.7	1.63	61.64	97.4				209.7	184.9	20.81	99.1			
57	14580	379.2	298.8	21.75	99.0	2.06	70.87	97.2				215.3	188.9	18.77	99.0			
58	6673	380.9	298.4	21.80	99.0	1.79	33.30	94.9				178.4	161.1	24.41	99.4			
59	10007	381.5	287.0	21.53	98.2	2.62	47.12	94.7				194.8	171.1	22.70	99.2			
60	11820	379.8	299.9	21.34	99.0	1.56	54.77	97.2				202.4	175.0	21.67	99.0			
61	11480	380.5	302.8	21.00	99.1	1.55	55.79	97.3				203.3	178.4	21.57	99.0			
62	15860	379.7	299.7	20.63	99.0	2.19	80.02	97.3				221.9	197.6	17.87	99.3			

TABLE 10 SERIES E AND F

	Thomas calorimeter								Exhaust from engine										
									Separating cal.			Throttling cal.							
No. test	Watt hr.	Steam temperature, deg. fahr.	Cal. discharge temperature deg. fahr.	Cal. discharge water lb.	Quality per cent	No. 1 Combined quality per cent	No. 2. combined quality per cent	Average quality per cent	Moisture lb.	Flow lb.	Quality per cent.	Steam temperature deg. fahr.	Cal. discharge temperature deg. fahr.	Cal. discharge press. in. mercury	Quality per cent	Combined quality per cent.	Quality by separator water and turb. steam quality per cent		
38	6600	229.2	414.6	93.90	84.1	92.2		90.2											
39	5623	217.6	430.6	84.10	86.3	90.7		89.4											
40	4758	216.7	429.9	93.60	92.4	91.1		91.5											
41	3242	216.3	412.7	70.20	93.2	91.2		91.9											
42	4268	216.7	426.8	110.20	94.4	91.4	91.2	93.0											
43	5000	216.7	408.3	116.50	94.3	91.5	92.1	92.6											
44	4575	216.4	424.6	88.80	91.9	91.2	93.2	92.1											
45	1519	195.4	445.2	30.90	94.9	92.0	92.5	93.1											
46	500	210.2	356.9	20.40	98.5	94.6	94.6	95.9											
47	350	203.3	454.2	27.40	95.6	95.8	94.5	95.3											
48	2100	191.8	420.0	37.92	91.7	93.9	92.0	92.5											
49						95.0	93.2	94.1											
50	2377	221.4	346.5	81.70	95.8	95.0	94.4	95.1											
51	2100	199.8	420.7	47.70	95.4	95.2	93.6	94.7											
52	2300	182.4	395.5	58.40	96.5	94.0	92.4	94.3											
53	2500	204.7	433.2	59.00	96.2	94.3	93.8	94.8											
54	650	213.3	276.7	44.05	98.0	95.7		96.9	2.53	26.90	91.4	213.8	180.5	23.29	98.7	90.2	89.6		
55	600	184.2	293.6	28.10	97.4	95.4		96.4	2.05	15.17	88.1	185.6	148.7	26.71	98.5	86.8	90.2		
56	600	209.7	268.5	44.40	98.1	96.5		97.3	2.53	21.70	89.5	209.5	167.7	25.41	98.6	88.2	90.3		
57	600	215.3	260.8	56.10	98.4	96.2		97.3	1.92	21.40	91.8	216.2	172.1	25.16	98.4	90.3	89.3		
58	450	178.4	267.7	24.90	97.0	94.4		95.7	1.88	17.12	90.7	177.9	148.3	25.80	98.8	89.0	89.7		
59	600	194.8	265.5	32.80	97.2	94.0		95.6	2.28	15.72	87.3	195.3	154.0	26.02	98.5	86.0	89.8		
60	600	202.4	274.2	39.90	98.2	96.3		97.3	2.49	19.17	88.6	203.4	163.4	25.76	98.5	87.3	90.3		
61	600	203.3	272.8	41.40	98.3	96.3		97.3	2.34	16.95	87.9	204.1	160.1	26.07	98.3	86.4	91.2		
62	700	221.9	274.3	55.40	98.1	96.6		97.4	2.11	24.65	92.1	222.8	178.4	24.73	98.5	90.7	89.8		

TABLE 11 SERIES E AND F

Test	West main steam deg. fahr	East main steam deg. fahr.	Average main steam deg. fahr.	West re-ceiver deg. fahr.	East re-ceiver deg. fahr.	Average re-ceiver deg. fahr.	East engine exhaust deg. fahr.	East separator inlet deg. fahr.	Separ-ator outlet deg. fahr.	Turb-ine bowl deg. fahr.	Con-denser deg. fahr.	Hot well water deg. fahr.	Circ. water injection deg. fahr.	Circ. water discharge deg. fahr.
38	381.0	380.2	380.6	297.0	297.4	297.2	230.5	230.1	229.2	228.5	90.90	71.20	37.66	57.28
39	384.1	382.8	383.4	297.3	297.4	297.4	218.7		217.6	217.0	94.60	76.23	39.85	62.51
40	380.3	380.1	380.2	296.1	297.5	296.8	218.0	217.6	216.7	216.1	84.45	70.97	32.03	51.84
41	382.4	381.4	381.9	297.0	297.7	297.3	217.9	217.2	216.3	216.3	87.17	73.41	33.95	56.76
42	380.2	380.9	380.6	296.9	297.0	297.0	218.6	218.6	216.9	216.9	87.18	75.25	31.82	56.67
43	380.6	381.3	381.0	296.8	296.6	296.7	217.9		216.7	216.3	89.32	80.17	32.75	57.14
44	380.3	382.2	381.3	296.9	296.5	296.7	217.6		216.4	216.1	73.87	59.42	31.63	41.98
45	380.3	381.8	381.1	296.8	297.7	297.3	208.2		195.4	196.7	86.72	66.20	32.22	43.97
46	379.7	382.7	381.2	295.0	296.0	295.5	209.0		210.2	208.0	77.20	63.70	40.20	53.10
47	379.0	380.8	379.9	295.3	296.0	295.6	205.0		203.3	204.0	80.00	63.00	36.00	46.85
				297.1	296.4	296.7	193.7			192.5				
48	379.6	381.0	380.3	276.3	275.8	276.1	190.5		191.8	189.4	84.86	60.58	32.90	42.06
49	377.8	381.6	379.7	279.6	280.4	280.0	202.0		200.3	201.0	83.50	62.60	31.38	53.86
50	376.7	380.2	378.5	291.5	291.5	291.5	222.6		221.4	221.0	82.23	65.69	31.51	50.08
51	379.0	379.8	379.4	287.2	286.8	287.0	203.4		199.8	199.8	83.16	65.18	37.50	43.10
52	379.7	381.0	380.4	268.9	270.2	269.6	183.8		182.4	180.8	85.70	58.15	31.47	39.81
53	380.5	382.3	381.4	285.5	283.2	284.4	205.7		204.7	204.6	83.65	65.65	31.46	45.37
54	376.3	381.8	379.1	287.1	288.7	287.9	215.6		213.3	213.3	81.20	57.26	33.54	47.77
55	378.0	383.5	381.8	271.8	271.7	271.7	187.0		184.2	183.8	81.00	58.64	33.08	41.30
56	378.4	383.0	380.7	285.8	286.5	286.2	209.3		209.7	207.6	74.70	60.72	33.40	50.10
57	377.0	381.4	379.2	293.0	291.6	292.3	217.5		214.9	215.5	67.41	53.21	33.28	47.60
58	379.4	382.5	380.9	267.5	267.9	267.7	177.4		177.4	176.3	78.20	53.85	33.18	39.46
59	380.0	383.0	381.5	277.5	277.4	277.5	195.7		194.8	194.1	78.30	59.12	33.40	43.66
60	377.9	381.7	379.8	283.2	283.0	283.1	204.4		202.4	202.4	74.04	59.60	33.25	46.00
61	378.5	382.4	380.5	283.0	282.5	282.8	205.0		203.3	203.2	77.18	61.74	33.06	47.23
62	377.5	381.8	379.7	296.3	296.3	296.3	223.9		221.9	221.8	82.42	62.79	33.64	56.00

TABLE 12 SERIES E AND F

	Water per hour									Water rates					I.h.p.				
No.	Load kw.	Turbine water weighed lb. per hr.	Turbine water venturi lb. per hr.	Sep. and traps weighed lb. per hr.	Sep. water lb. per hr.	Traps Venturi lb. per hr.	Total engine water lb. per hr.	Dry steam engine lb. per hr.	Dry steam turbine lb. per hr.	Actual unit lb. per kw-hr.	Actual engine lb. per kw-hr.	Actual turbine lb. per kw-hr.	Corrected unit moisture only lb. per kw-hr.	Corrected unit total corrected lb. per kw-hr.		Average high pressure i.h.p.	Average low pressure i.h.p.	Total i.h.p.	Factor i.h.p. per kw.
38	16172	237480		7425	7175	250	244905	243700	214200	15.07	29.54	27.51	14.40	14.10		5640	6117	11757	1.404
39	13485	187193		9883	5881	4002	197076	193000	167400	14.32	24.76	28.38	13.48	13.10		5104	5847	10951	1.404
40	13038	170661		12271	6281	5980	182932	181500	156200	13.92	24.78	27.35	13.44	13.42		4931	5650	10581	1.447
41	12284	160229		12064	3628	8436	172293	170400	147200	13.88	24.57	27.51	13.39	13.28		4800	5306	10106	1.457
42	11252	147142		10927	2607	8320	158069	156100	136900	13.87	24.99	27.72	13.54	13.42		4250	4330	8580	1.374
43	10476	138766		9939	1801	7138	147153	145000	128500	13.85	24.90	27.91	13.47	13.21		4227	4280	8507	1.460
44	9408	122689		8387	227	8160	131076	129400	113000	13.75	26.19	25.53	13.32	13.59		3771	3490	7261	1.470
45	9712	121870		13160	4910	8250	135030	133300	113500	13.72	22.53	30.59	13.49	13.45		3819	4367	8186	1.385
46	12700	160960		18874	11242	7632	179834	177700	154400	13.99	24.75	27.38	13.62	13.77		4994	6313	11307	1.575
47	11940	142740		17385	8935	8450	160125	158700	136000	13.30	22.49	28.45	13.15	13.31		4675	5736	10411	1.475
48	9306	114372		12555	4744	7811	126927	125100	105800	13.44	21.34	31.84	13.25	13.25		4129	4321	8450	1.441
49	10940	134785		16565	8257	8308	151350	149700	126900	13.69	22.40	29.50	13.39	13.46		5039	4545	9584	1.444
50	15498	202656		19161	16661	2500	221817	220400	192900	14.22	26.99	26.55	13.96	14.03		5784	5825	11609	1.421
51	11240	133462		16689	8399	8290	150151	148100	126500	13.19	21.95	28.89	13.04	13.04		4585	5244	9829	1.456
52	7200	89158		10861	7170	3691	100019	98400	84080	13.67	20.75	35.04	13.52	13.43		3662	3478	7140	1.505
53	11927	143897		17901	8164	9737	161798	159500	136500	13.38	22.57	28.22	13.13	13.08		4995	4897	9892	1.400
54	14173	176565		19180	12930	6250	195745	193600	171050	13.66	24.75	27.22	13.54	13.81		5430	5370	10800	1.400
55	8347	99210		13733	6183	7550	112943	111400	95620	13.34	20.60	32.85	13.23	13.28		3907	3792	7699	1.425
56	13033	158112		18849	11159	7690	176961	174700	153850	13.40	23.43	27.72	13.28	13.47		5115	5120	10235	1.373
57	14580	182508		20011	14741	5270	202599	200700	177600	13.75	25.19	26.95	13.65	14.00		5376	5673	11049	1.388
58	6673	81533		11225	4900	6325	92958	91800	78000	13.76	20.78	35.27	13.65	13.87		3282	3170	6452	1.460
59	10007	120863		14578	6478	8100	135441	133050	115600	13.30	21.48	30.38	13.13	13.39		4452	4294	8746	1.418
60	11820	141930		17833	9873	7960	159763	158200	138100	13.38	22.84	28.41	13.28	13.61		5108	4796	9904	1.431
61	11480	143958		17101	8791	8310	161059	159600	141500	13.92	24.45	24.22	13.75	13.95		4728	4594	9322	1.414
62	15860	206603		19762	15705	4057	226365	224200	201300	14.14	26.58	26.56	13.99	13.99		5750	6538	12288	1.456

TABLE 13 SERIES E AND F

No.	Total load	B.t.u. distribution:unit is 1,000,000 B.t.u.															
		Supplied to unit		Supplied to turb. only		Engine kw. output		Turb. kw. output		Total kw. output		To condenser		To hot well		Lost by radiation etc.	
test	kw.	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent	B.t.u.	per cent
38	16172	292.0	100	252.5	86.5	28.61	9.8	26.58	9.1	55.19	18.9	216.6	74.2	9.31	3.2	10.89	3.7
39	13485	232.6		196.6	84.6	26.36	11.3	19.88	8.6	46.27	19.9	168.4	72.4	8.28	3.6	9.64	4.1
40	13038	218.0		182.5	83.7	24.97	11.5	19.49	8.9	44.46	20.4	156.4	71.7	6.65	3.1	10.53	4.8
41	12284	204.7		171.8	83.9	23.67	11.6	18.25	8.9	41.92	20.5	146.9	71.7	6.64	3.2	9.23	4.5
42	11252	187.7		159.5	85.0	21.35	11.4	16.95	9.0	38.37	20.5	136.2	72.5	6.36	3.4	6.85	3.7
43	10476	174.5		149.8	85.9	19.93	11.4	15.76	9.0	35.68	20.5	127.3	73.0	6.69	3.8	4.77	2.7
44	9408	155.8		131.9	84.6	16.87	10.8	15.12	9.7	32.09	20.6	113.4	72.7	3.36	2.2	7.03	4.5
45	9712																
46	12700																
47	11940																
48	9306	150.5		122.3	81.3	20.14	13.4	11.46	7.6	31.61	21.0	107.6	71.5	3.27	2.2	8.06	5.4
49	10940																
50	15498	264.2		224.2	84.8	27.95	10.6	24.85	9.4	52.56	19.9	192.5	72.8	6.83	2.6	12.05	4.6
51	11240	178.0		146.0	81.8	23.16	13.0	15.05	8.4	37.85	21.3	126.5	70.9	4.43	2.5	8.84	5.0
52	7200	118.4		96.41	81.4	16.25	13.7	8.26	7.0	24.37	20.6	85.8	72.5	2.33	2.0	5.74	4.8
53	11927	191.8		157.8	82.3	24.16	12.6	16.53	8.6	40.66	21.2	136.4	71.2	4.84	2.5	9.84	5.1
54	14173	232.4		197.8	83.4	26.76	11.3	21.53	9.1	48.29	20.4	171.8	72.4	4.46	1.9	7.84	3.3
55	8347	133.8		109.55	81.9	18.48	13.8	9.97	7.5	28.45	21.3	97.9	73.2	2.64	2.0	5.77	4.3
56	13033	210.0		175.5	83.6	25.46	12.1	18.97	9.0	44.43	21.2	151.9	72.3	4.54	2.2	9.04	4.3
57	14580	240.7		205.4	85.4	27.20	11.3	22.51	9.4	49.74	20.7	170.9	74.4	3.87	1.6	8.10	3.4
58	6673	110.4		89.25	80.9	15.13	13.7	7.59	6.9	22.73	20.6	79.8	72.4	1.78	1.6	6.02	5.5
59	10007	160.0		133.6	83.2	21.13	13.2	12.99	8.1	34.12	21.3	116.7	72.9	3.28	2.1	5.87	3.7
60	11820	189.8		158.9	83.7	23.67	12.5	16.62	8.8	40.29	21.2	138.4	72.9	3.92	2.1	7.23	3.8
61	11480	191.8		161.5	84.2	22.47	11.7	16.70	8.7	39.17	20.4	140.5	73.3	4.28	2.2	7.83	4.1
62	15860	269.2		232.2	86.3	28.82	10.7	25.31	9.4	54.11	20.1	200.5	74.5	6.36	2.4	8.18	3.0

TABLE 14 SERIES E AND F

No. test	Load unit	Efficiencies									Heat to condenser			Remarks
		Rankine efficiencies			Thermal effic. ref'd to Rankine			Thermal eff. recov. hot well water			Ratio condenser water to steam	B.t.u. per sq. ft. per sec.	B.t.u. per sq. ft. per sec. per deg. rise	
		Engine	Turb.	Unit	Engine	Turb.	Unit	Engine	Turb.	Unit				
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent				
38	16172	16.7	18.2	30.1	70.3	60.0	65.0	11.7	10.9	19.5	53.5	2.58	0.0594	Constant nozzle pressure auxiliaries exhaust to heaters
39	13485	16.8	16.8	29.1	81.5	63.5	70.5	13.7	10.7	20.5	48.2	1.99	0.0459	" " " " " "
40	13038	17.8	18.4	30.8	76.9	60.0	60.5	13.7	11.0	21.1	52.9	1.86	0.0437	" " " " " "
41	12284	17.6	17.7	30.4	78.5	62.3	69.7	13.8	11.0	21.2	46.4	1.77	0.0428	" " " " " "
42	11252	17.4	17.8	30.3	76.4	61.8	70.1	13.6	11.0	21.2	42.7	1.65	0.0384	" " " " " "
43	10476	17.3	17.7	30.2	78.9	60.5	70.7	13.6	11.4	21.4	44.2	1.53	0.0345	" " " " " "
44	9408	17.6	18.8	29.4	73.2	62.5	71.8	12.9	11.7	21.1	107.7	1.37	0.0369	" " " " " "
48	9306	20.5	15.6	30.5	74.9	61.2	71.0	15.4	9.5	21.7	118.0	1.26	0.0266	Variable nozzle pressure auxiliaries exhaust to heaters
51	11240	19.7	16.4	30.8	76.7	53.6	72.0	15.1	10.5	22.2	150	1.28	0.0298	" " " " " "
54	14173	18.2	18.7	31.2	74.5	59.1	68.1	13.6	11.1	21.2	77.1	2.08	0.0512	" " " " " "
55	8347	21.2	17.5	30.5	74.6	52.6	71.5	15.8	9.2	21.8	11.2	0.92	0.0210	" " " " " "
56	13033	18.2	18.4	31.0	78.5	59.4	69.0	14.2	10.9	21.7	63.4	1.87	0.0566	" " " " " "
57	14580	18.0	19.5	32.2	74.0	57.0	65.4	13.6	11.1	21.0	77.5	2.16	0.0800	" " " " " "
58	6673	21.3	14.6	31.4	73.2	59.0	67.0	15.6	8.6	21.0	15.3	2.55	0.0608	" " " " " "
59	10007	19.5	16.7	31.3	78.5	60.0	69.8	15.3	10.0	21.8	108	1.41	0.0336	" " " " " "
60	11820	19.5	20.2	32.2	74.8	52.9	67.6	14.5	10.7	21.8	82.9	1.67	0.0485	" " " " " "
61	11480	19.6	17.6	31.4	69.8	60.4	66.9	13.7	10.7	21.0	108	2.40	0.0885	Variable nozzle pressure auxiliaries exhaust into separator
62	15860	17.2	18.7	30.0	74.0	59.4	68.9	12.7	11.1	20.7	49.0	2.52	0.0670	" " " " " " heaters

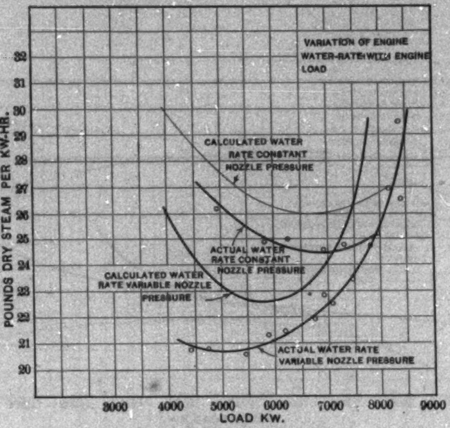


FIG. 13.—Series E and F

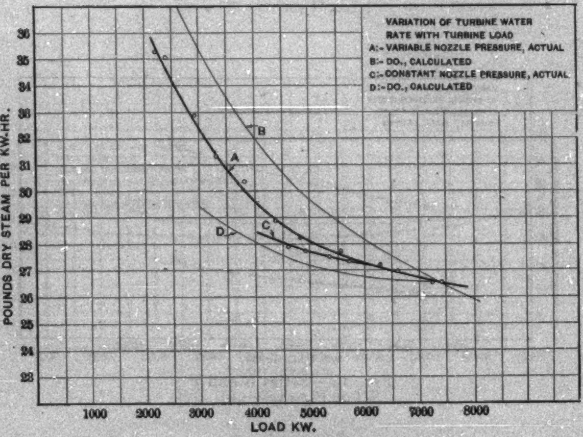


FIG. 14.—Series E and F

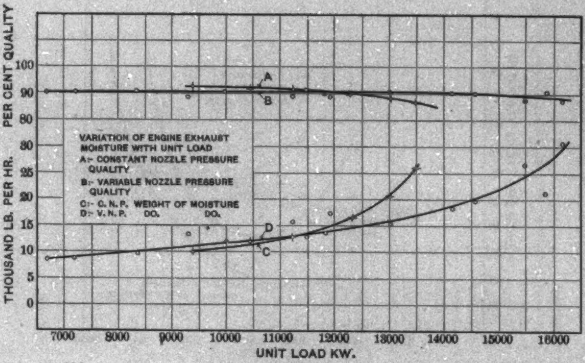


Fig. 15.—Series E and F

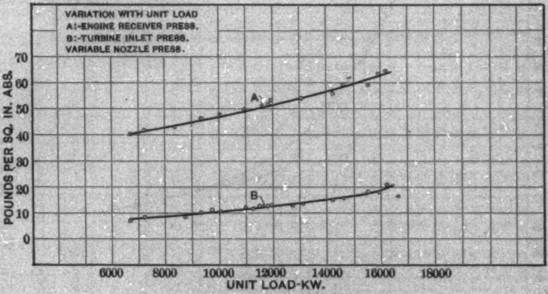


Fig. 16.—Series E and F

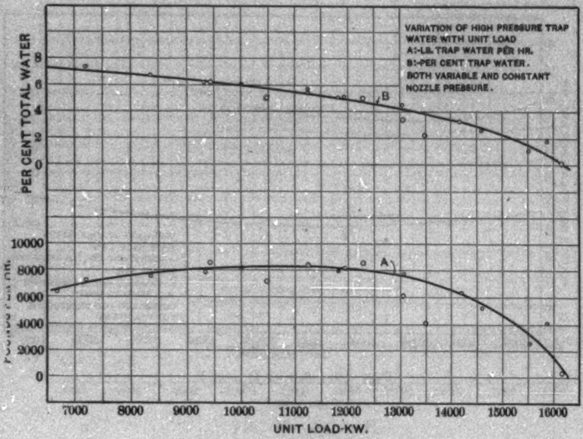


FIG. 17.—Series E and F

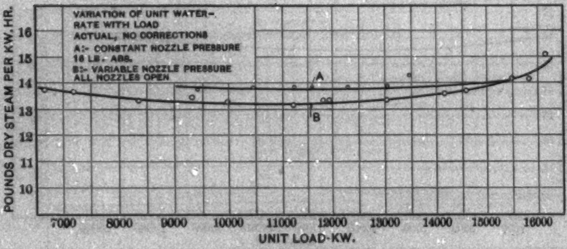


FIG. 18.—Series E and F

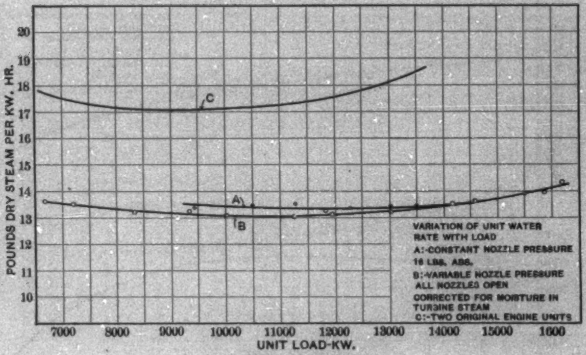


FIG. 19.—Series E and F

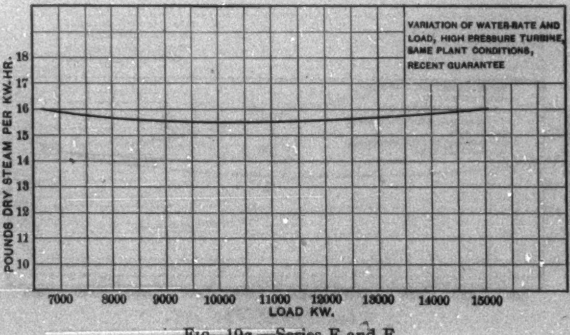


FIG. 19*a*.—Series E and F

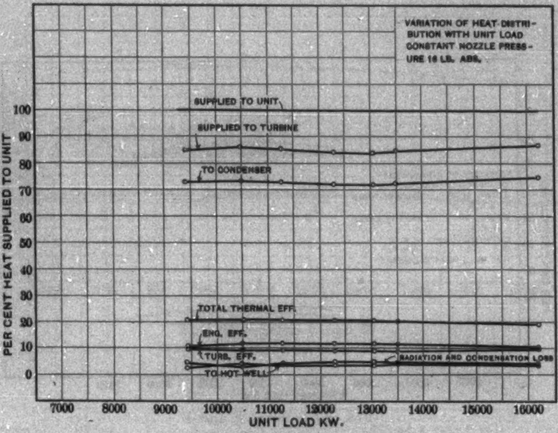


FIG. 20.—Series E

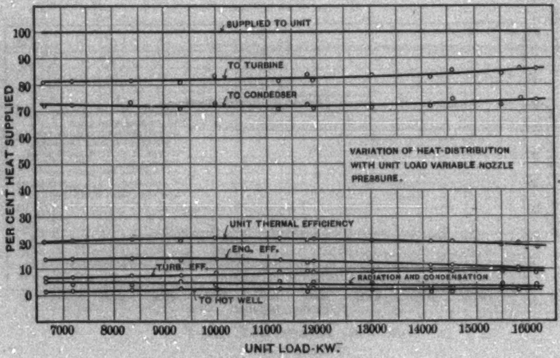


FIG. 21.—Series F

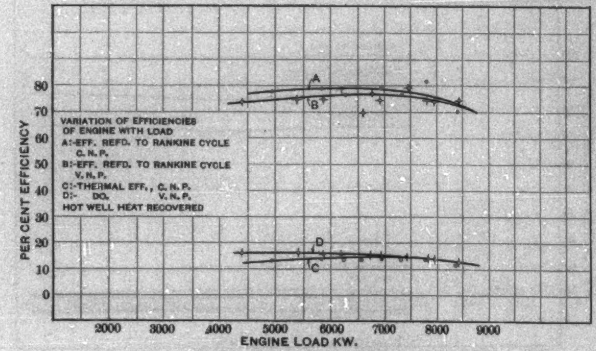


FIG. 22.—Series E and F

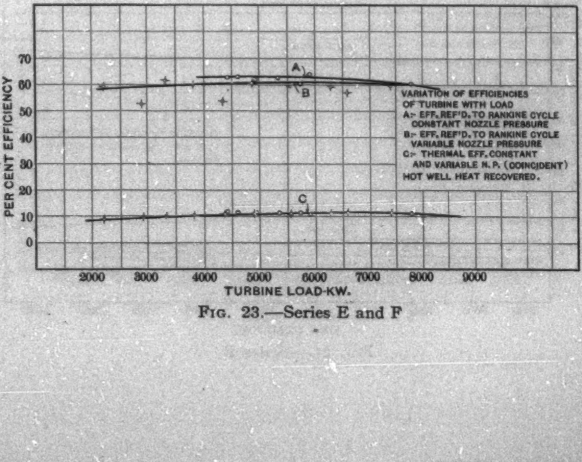


FIG. 23.—Series E and F

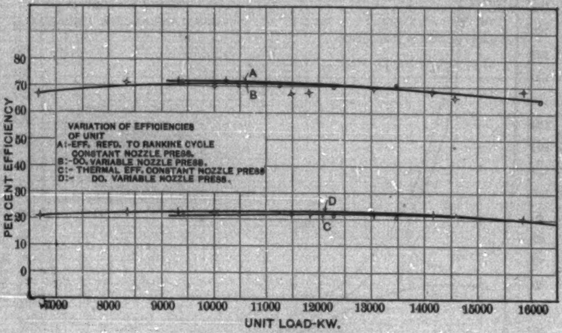


Fig. 24.—Series E and F

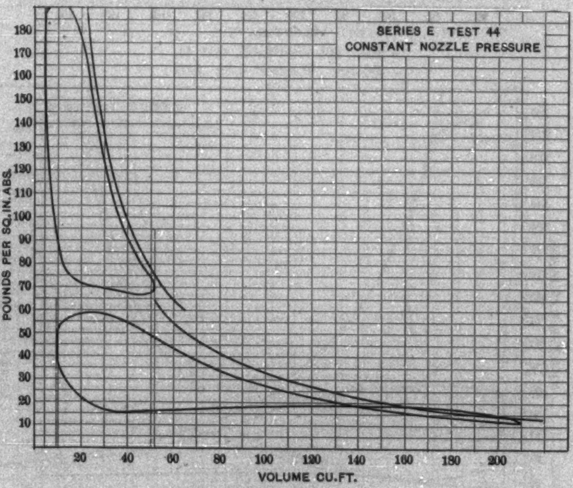


Fig. 25.—Series E, test 44

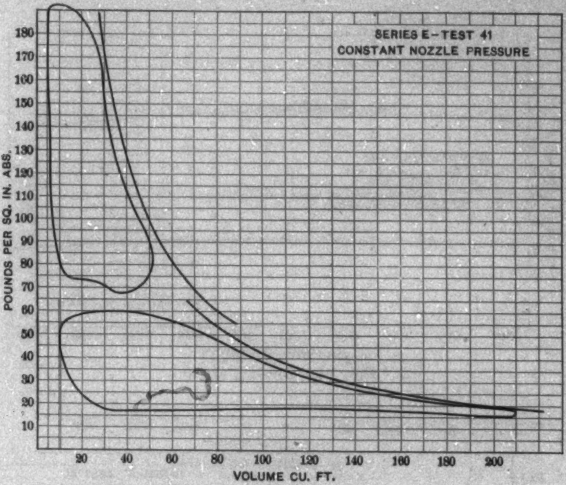


FIG. 26.—Series E, test 41

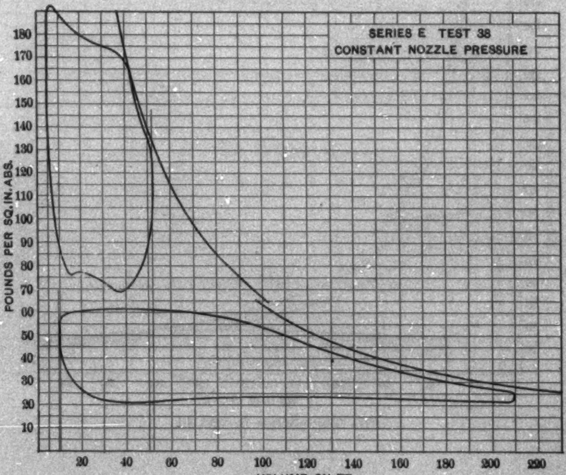


FIG. 27.—Series E, test 38

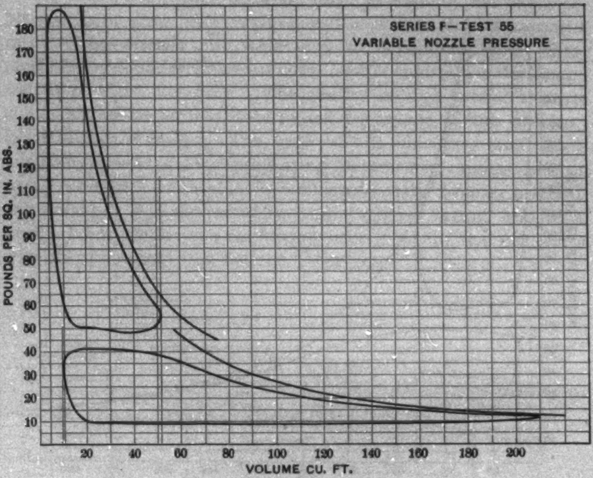


FIG. 28.—Series F, test 55

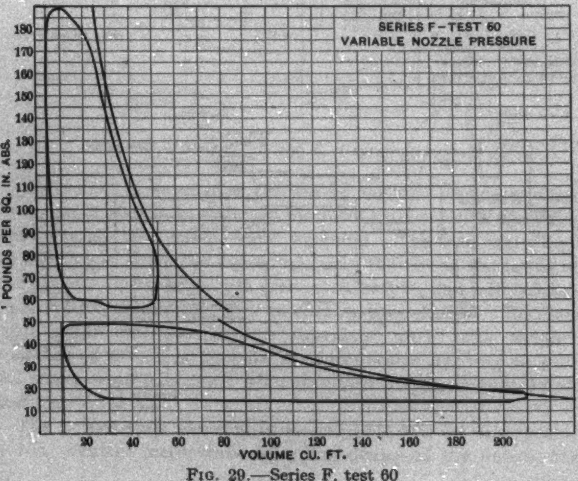


FIG. 29.—Series F, test 60

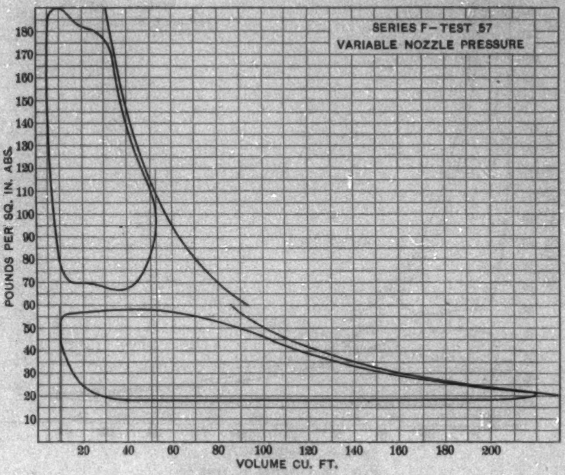


Fig. 30.—Series F, test 57

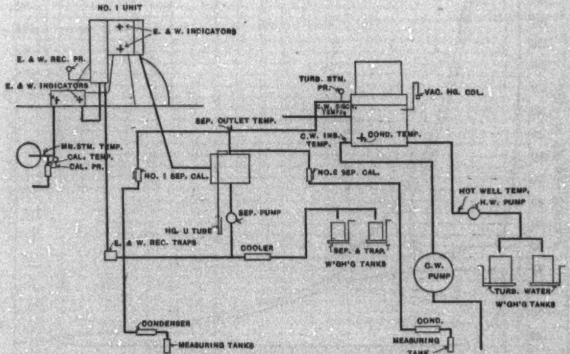

NO. 1 UNIT
E. & W. INDICATORS
E. & W. REC. PR.
E. & W. INDICATORS
MN. STM. TEMP.
CAL. TEMP.
CAL. PR.
SEP. OUTLET TEMP.
TURB. STM. PR.
VAC. HG. COL.
C.W. DISCH. TEMP.
C.W. INS. TEMP.
COND. TEMP.
NO. 1 SEP. CAL.
NO. 2 SEP. CAL.
SEP. PUMP
HG. U TUBE
E. & W. REC. TRAPS
COOLER
SEP. & TRAP W'GH'G TANKS
HOT WELL TEMP.
H.W. PUMP
C.W. PUMP
TURB. WATER W'GH'G TANKS
CONDENSER
MEASURING TANKS
COND.
MEASURING TANK

Fig. 31.—Series C, diagramatic test layout

The first point which presents itself in view of the remarkable results of these tests, is the question of accuracy of measurement. The actual unit water-rate is dependent upon three factors only: quality of steam entering the engine, kw. load, and weight of water per hour. The quality of high-pressure steam is easily and accurately determined by means of the ordinary throttling calorimeter. The load on the machines was determined by means of nine integrating meters: two meters each on turbine, engine and total load, connected by the 2-meter method; one balanced 3-phase meter each on turbine, engine, and total load. Each meter was calibrated once a week, and the error was always within one-half of 1 per cent.

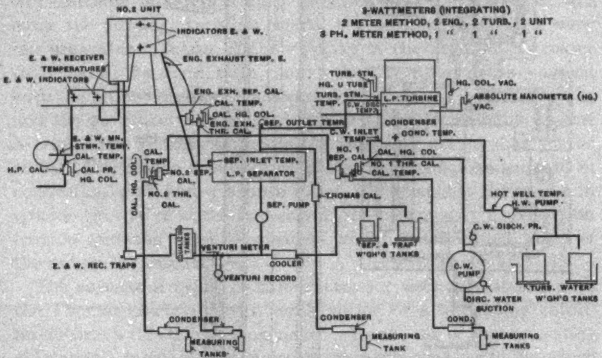

NO.2 UNIT
INDICATORS E. & W.
E. & W. RECEIVER TEMPERATURES
E. & W. INDICATORS
ENG. EXHAUST TEMP. E.
ENG. EXH. SEP. CAL.
CAL. TEMP.
CAL. HG. COL.
ENG. EXH. THR. CAL.
SEP. OUTLET TEMP.
E. & W. MN. STMN. TEMP.
CAL. TEMP.
H.P. CAL.
CAL. PR. HG. COL.
CAL. TEMP
CAL. HG. COL.
NO.2 SEP. CAL.
NO.2 THR. CAL.
SEP. INLET TEMP.
L.P. SEPARATOR
SEP. PUMP
QUALITY TANKS
VENTURI METER
COOLER
VENTURI RECORD
E. & W. REC. TRAPS
CONDENSER
MEASURING TANKS
9-WATTMETERS (INTEGRATING)
2 METER METHOD, 2 ENG., 2 TURB., 2 UNIT
3 PH. METER METHOD, 1 " 1 " 1 "
TURB. STM. HG. U TUBE
TURB. STM. TEMP.
C.W. DISCH. TEMP.
L.P. TURBINE
HG. COL. VAC.
ABSOLUTE MANOMETER (HG.) VAC.
CONDENSER
COND. TEMP.
C.W. INLET TEMP.
NO. 1 SEP. CAL.
CAL. HG. COL
NO. 1 THR. CAL.
CAL. TEMP.
THOMAS CAL.
SEP. & TRAP W'GH'G TANKS
HOT WELL TEMP.
H.W. PUMP
C.W. DISCH. PR.
C.W. PUMP
CIRC. WATER SUCTION
TURB. WATER W'GH'G TANKS
CONDENSER
MEASURING TANK
COND.
MEASURING TANKS

FIG. 32.—Series D, E and F, diagrammatic test layout

The weight of water from the turbine hot-well was determined by a pair of 40,000-lb. standard platform scales, with a recording device in addition to the hand weighing. The load was about 25,000 lb. per scale, the limitation being the size of the tanks on the scales. These scales are graduated to 5 lb. and will balance to 2 or 3 lb., so that the error in reading is negligible. Receiver trap water and low-pressure separator water was weighed together on a pair of 2000-lb. platform scales, reading to ½ lb. All scales were calibrated with standard 50-lb. weights before testing.

The actual trap water weight was obtained by interposing a 1-in. Venturi meter with recording device in the line to the scales; this was also calibrated by scales and found correct to less than 1 per cent, and the low-pressure separator water obtained by difference.

For examination of thermodynamic conditions within the machines, the most important determination is that of quality of the low-pressure steam to the turbine, since on this depends one of the important corrections to guaranteed conditions. There were no experimental data available that we could discover, bearing on low-pressure quality determinations, so the investigation was made incidental to the tests, from which the following

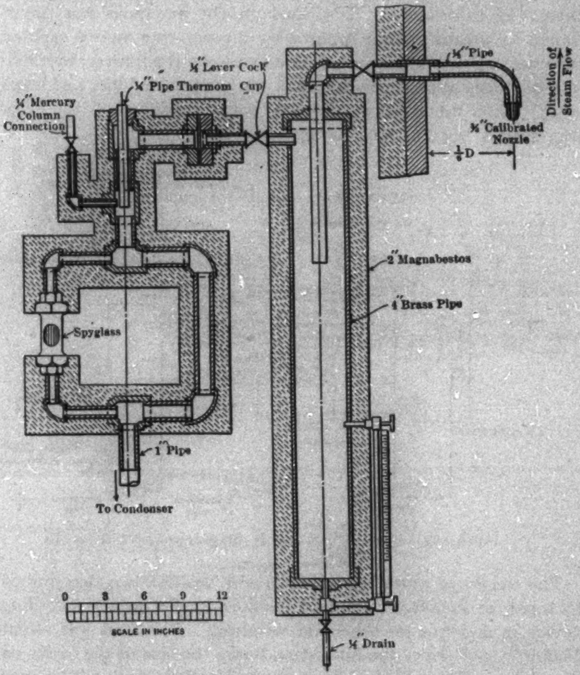

¼" Lever Cock
¼" Pipe Thermom Cup
¼" Mercury Column Connection
¼" Pipe
Direction of Steam Flow
¼" Calibrated Nozzle
⅛D
2" Magnabestos
4" Brass Pipe
Spyglass
1" Pipe
To Condenser
0 3 6 9 12
SCALE IN INCHES
¼" Drain

FIG. 33.—Low pressure separating-throttling calorimeter

was established. The ordinary standard perforated pipe sampler is absolutely worthless in giving a true sample, and it is vital that the sample be abstracted from the main without changing its direction or velocity until it is safely in the sample pipe and entirely isolated from the rest of the steam. Multiple orifice nozzles are of no use, as in all cases one orifice will supply practically all the steam, leaving the others useless. After much experimenting with various styles of samplers, all of which were failures the single orifice curved tube (Fig. 33) was adopted.

The reason for failure of other styles is plain; if any sudden turn is made by the wet steam in entering the sample nozzle, the entrained moisture, by reason of its immensely greater specific gravity and slight skin friction in the tenuous surrounding fluid, will continue with unchanged direction and a dry sample will enter the nozzle. In other words, the sampler becomes a very fair separator. Again, if the velocity in the sampler is greater than that in the main, even though there be no separating action with the proper sampler, the steam will accelerate into the nozzle, and the moisture will not, giving a dry sample; and the reverse is true if the velocity is less in the sampling nozzle than in the main. The reason this very simple action has not been noted in connection with high-pressure steam is the smaller difference in specific gravity of water and steam, the enormously greater skin friction and the small percentage and highly-divided state of the moisture present.

The successful types of calorimeter for very wet steam were the Thomas electric, and a combination of a separating calorimeter with a throttling calorimeter. By the use of the separating calorimeter most of the moisture was removed, and the small remainder was registered by the throttling calorimeter. At first glance it seems as if, with an initial pressure of 12 lb. to 20 lb. absolute, the throttling calorimeter has no capacity, but by putting a vacuum of 28 in. on the discharge side of the calorimeter, an available heat is obtained sufficient to evaporate 2 or 3 per cent of moisture. When the moisture became less than this, we used the throttling calorimeter direct, eliminating the separating calorimeter altogether. The separating-throttling combination was afterward tested for radiation loss and found to lose less than 0.1 per cent at proper flow. Fig. 33 shows this combination instrument. The large size is necessary on account of the very high specific volume of steam at low pressure.

Referring to Fig. 33, the $\frac{3}{8}$-in. brass nozzle on the sampler is arranged to point in exactly the opposite direction to the steam flow; the lip of the nozzle is filed to a knife-edge to avoid disturbing the steam current around the sampler mouth by impact and eddies against a sensibly thick lip. The diameter of the brass nozzle is carefully measured and, if necessary, reamed smooth. This form of sampler fulfills the requirements noted above; it takes out the sample without disturbing its direction, by virtue of its position and knife-edged orifice, and the velocity can be kept correct by determining the flow from the following simple formula:

$$w = \frac{Wa}{A}$$

where

w = lb. per hr. flow through calorimeter.
W = lb. per hr. flow through steam main.
a = area of sampler nozzle.
A = area of main.

The sampler is allowed to extend into the pipe one-sixth of the pipe diameter, which has been found to give practically true average flow.

The ½-in. valve at the sampler is opened wide, and the ½-in. lever cock between separating and throttling calorimeters is used to regulate the flow, the throttling action taking place at this point. The rest of the calorimeter is under vacuum, the discharge being connected to a small cooler to condense the steam and then to a volumetric measuring tank. The top of this tank, which is entirely closed except for the pipe connections, was connected with the turbine condenser by a ¼-in. pipe, which gave an available vacuum of over 28 in. without affecting the measuring in any way. The spy-glass is very useful in proving that the calorimeter is working properly, for when the superheat in the throttling calorimeter gets below 6 or 8 deg. it sometimes happens that some moisture goes by, in which case the spy-glass immediately shows it up, no matter how small the quantity. As the spy-glass is most conveniently made of ¾-in. gage glass, more area is required to take away the steam from the calorimeter, and this was done by adding a by-pass of 1-in. pipe around the spy-glass. This allows free flow to take place and does not affect the function of the glass.

The percentage of moisture taken out by the separating portion of the instrument divided by the total percentage of moisture gives the efficiency of the separating calorimeter, which turns out to be much lower than is ordinarily supposed, from 60 to 80 per cent.

For the rest of the measurements steam pressures throughout were taken with high grade thermometers, graduated to 1 deg. and in many cases as low as 0.2 deg., as these are in every case preferable to gages for saturated steam. All pressures below 15 lb. gage and all vacua were measured by mercury column, in addition to temperatures.

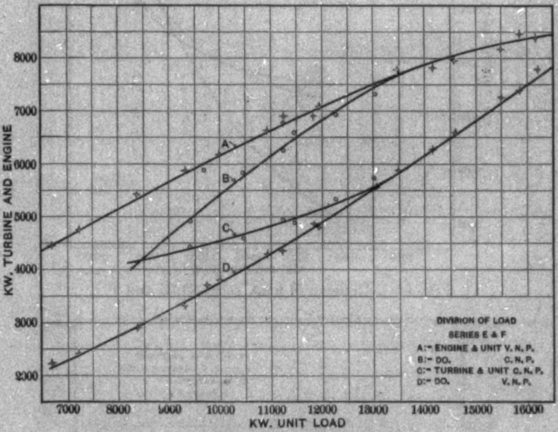


FIG. 34.—Division of load, series E and F

Table 1, Steam to Auxiliaries, includes for tests 25, 22, 24, 21, 23 and 26, the circulating water pump steam only; test 27, circulating water pump and dry vacuum pump; test 29, circulating water pump, dry vacuum pump and boiler feed pump; test 30, boiler feed pump alone.

Fig. 11 and Fig. 11a show variation of points is due to errors in earlier low-pressure calorimetry, before the standard instruments were settled upon.

Table 12, the column of Unit Water-Rate Total Correction, is based on a standard vacuum of 28.72 in. instead of 28.5 in., as the higher figure was the average vacuum of the series of tests. Consequently the absolute amount of correction was reduced, which is of course very desirable, in view of the uncertainty of correction factors.

In Fig. 14 these water rates are uncorrected for moisture, etc.

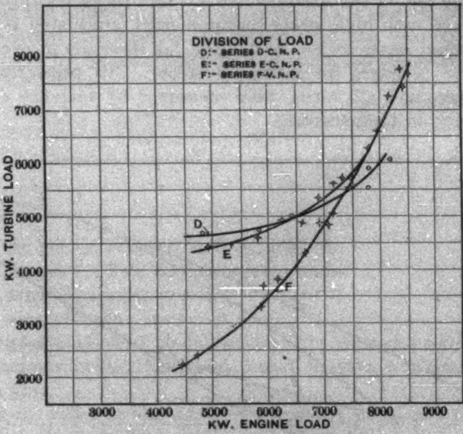


FIG. 35.—Division of load, series D, E and F

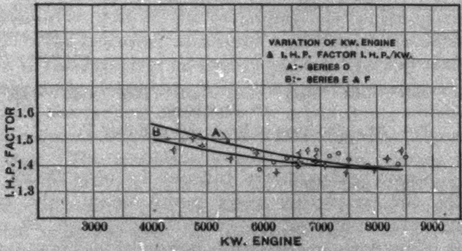


FIG. 36.—Variation of kw-engine and i.h.p. factor

In Fig. 32 the calorimeters were drawn for the sake of clearness, as if they were situated at some distance from the sampling points; actually they were, as in Fig. 1.

Figs. 34 and 35 and 36 serve to show the variation in load between engine and turbine, and the effect of change of efficiency of the two machines.

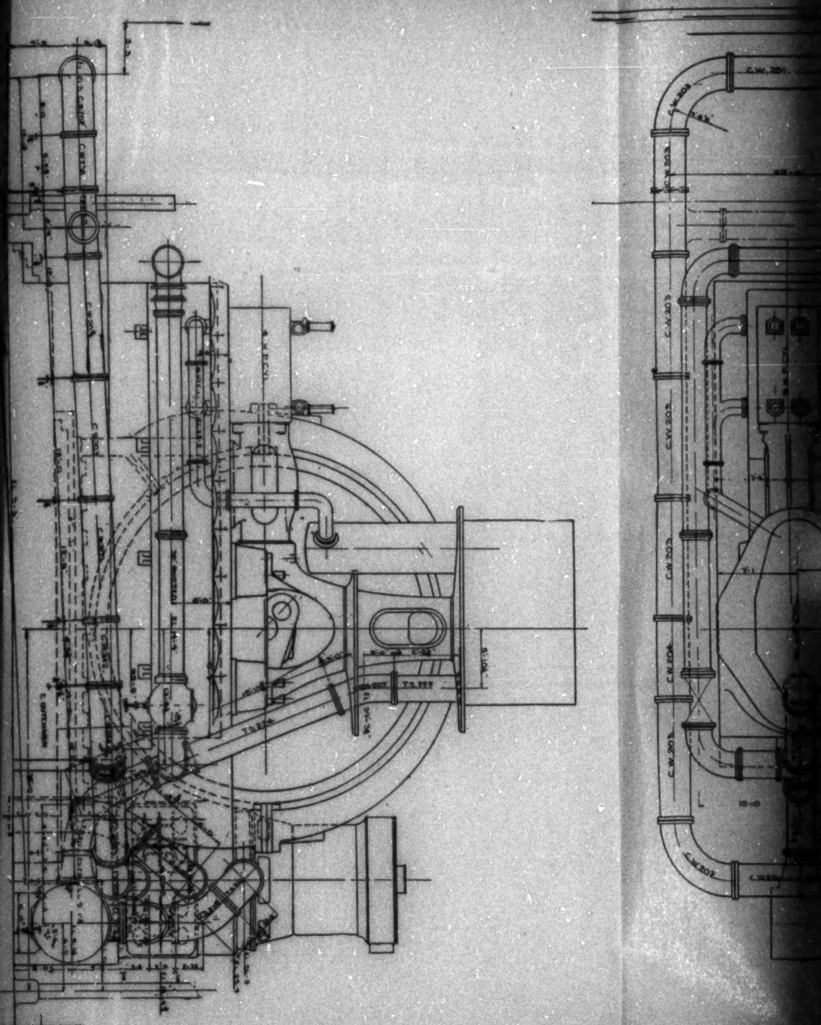
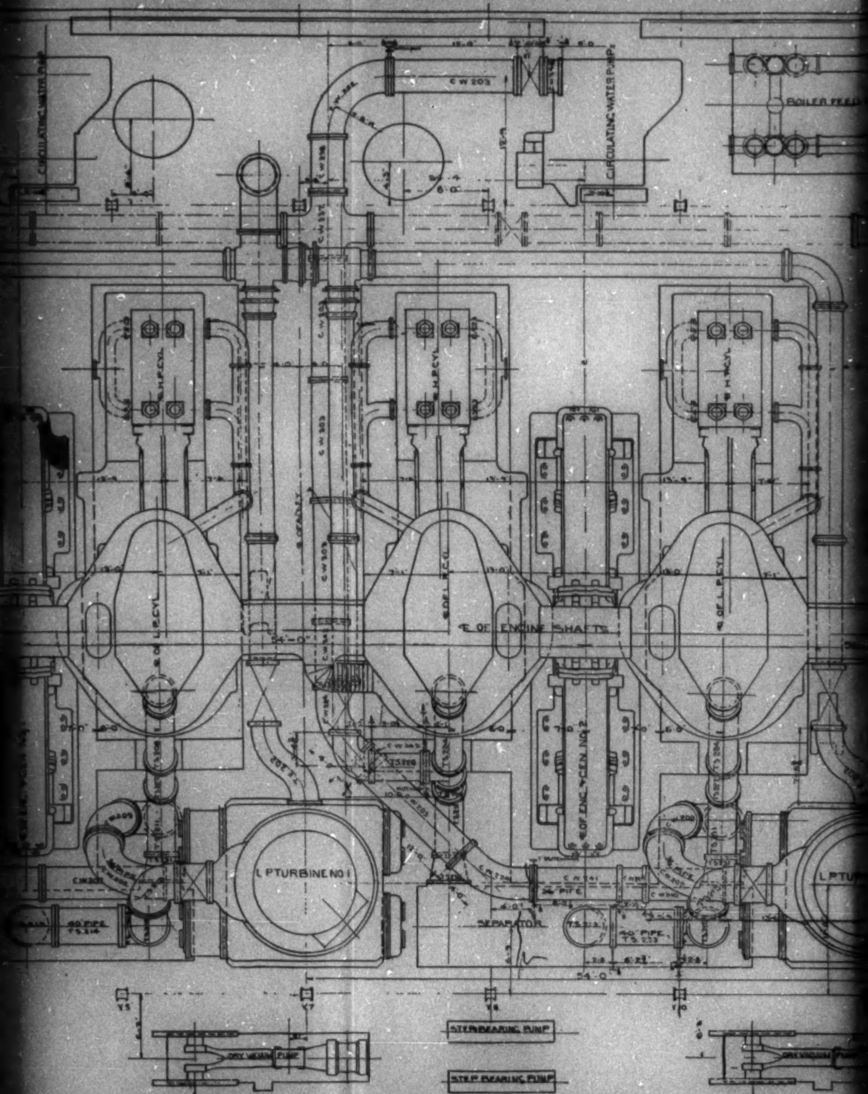

C.W. 201
C.W. 202
C.W. 203
C.W. 204
T-1
18-0

PLATE 1.—End


CIRCULATING WATER PUMP
C W 203
CIRCULATING WATER PUMPS
BOILER FEED
H.P. CYL
H.P. CYL
H.P. CYL
L.P. CYL
L.P. CYL
L.P. CYL
E OF ENGINE SHAFTS
54'-0"
E OF ENG & GEN NO 2
L P TURBINE NO 1
L P TU
36" PIPE
SEPARATOR
40" PIPE TS 214
40" PIPE TS 233
54'-0"
DRY VACUUM PUMP
STEP BEARING PUMP
STEP BEARING PUMP
DRY VACUUM PUMP

of engine and low-pressure turbine units; 59th St. Station, Interborough Rapid Transit Company

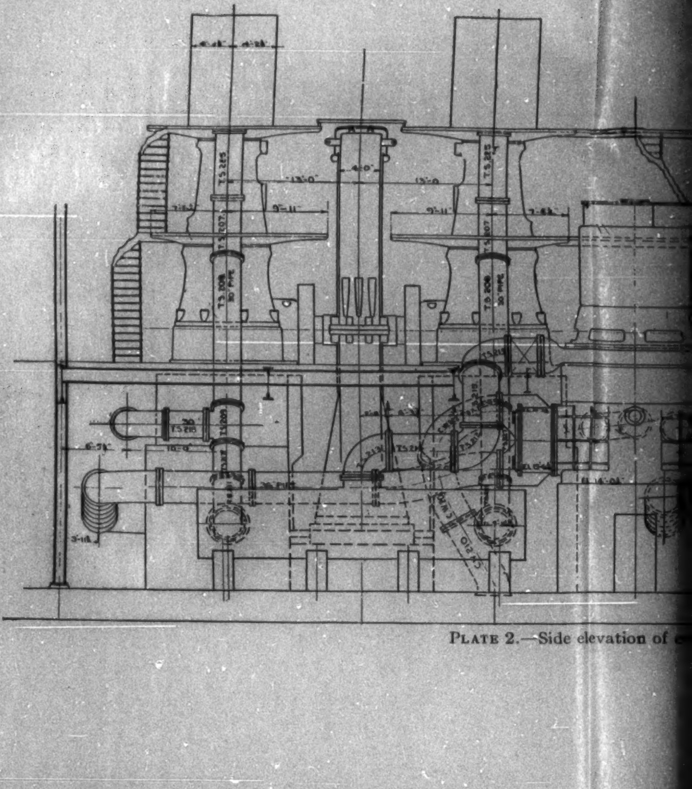
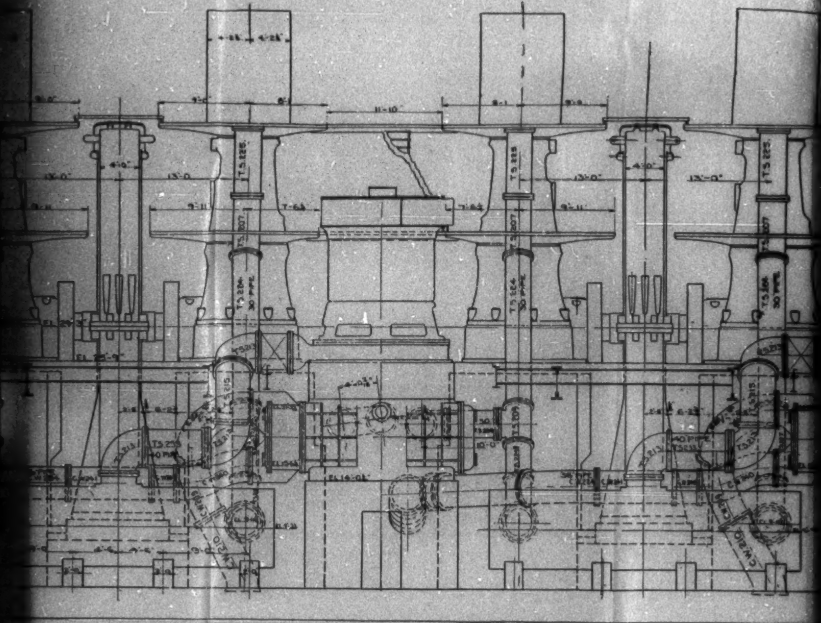

4'-2½"
4'-2½"
T.S. 225
T.S. 225
13'-0"
13'-0"
4'-0"
7'-6½"
9'-11"
9'-11"
7'-6½"
T.S. 207
T.S. 207
T.S. 208
30" PIPE
T.S. 208
30" PIPE
T.S. 219
T.S. 218
30
T.S. 218
T.S. 209
6'-3½"
16'-0"
T.S. 214
T.S. 212
36" PIPE
C.W. 210
3'-1½"

PLATE 2.—Side elevation of



9'-0"
9'-0"
8'-1"
11'-10"
8'-1"
9'-0"
4'-0"
13'-0"
13'-0"
9'-11"
9'-11"
7'-6½"
7'-6½"
T.S. 225
T.S. 207
T.S. 204
30 PIPE
T.S. 213
T.S. 215
T.S. 209
40 PIPE
C.W. 210
EL 29'-3"
EL 25'-9"
EL 15'-0½"
4'-6"
4'-6"

ssure turbine units: 59th Street Station, Interborough Rapid Transit Company

FORMULAE AND CONSTANTS

Engine.

Two high-press. cylinders 42 by 60 in., 9-in. rod
Two low-press. cylinders 86 by 60 in., 10-in. rod.
Rev. per min. 75.
Two 14-in. steam mains.
Two 16-in. high-press. exhausts.
Two 30-in. low-press. exhausts.
Clearances.
High-press. head 9.5 per cent. Crank 10 per cent.
Low-press. head 4.77 per cent. Crank 4.78 per cent.
Average total volume high press. 51.7 cu. ft.
low-press. 209.9 cu. ft.
Average displacement high press. 47 cu. ft.
low press. 200.3 cu. ft.
i.h.p. constant. High press. 15.38. Low press. 65.57 (average)

All combined cards worked out on average basis. Marks and Davis tables used for steam data.

Table II.

E_r = Rankine thermal efficiency, cyclic.
E_t = Engine thermal efficiency.
H_1 = Heat in initial steam at press. p_1 quality x (total per hr.)
H_2 = Heat in steam at p_2, x_2, after adiabatic expansion from p_1, x_1, (total per hr.)

$$\frac{H_1 - H_2}{H_1} = E_r \qquad E_t = \frac{\text{kw.} \times 3412}{H_1} \qquad \frac{E_t}{E_r} = E_e$$ = engine efficiency referred to rankine cycle.

No heat recovered.

Table III.

p_a, V_a = pressure and volume at high press. cut off, lb. per sq. in. and cu. ft.
p_c, V_c = press. and volume at high press. compression.
W_a = specific density at p_a,
W_c = specific density at p_c.
$V_a W_a - V_c W_c = W$, lb. indicated steam per stroke.

$$\frac{W \times 75 \times 4 \times 60}{\text{i.h.p.}}$$ = indicated water rate (I.W.R.)

I.W.R. $(1+y)$ = A.W.R., (actual water rate)
$y = 1.29\ (r - 1.06)$ kw. $\times\ 1.465$ = i.h.p.

$$r = \frac{51.7}{V_a}$$ for high press. cycle = ratio of expansion.

Table IV.

Q_e = Total dry steam per hr. to engine.

Q_f = Trap water per hr.

X_e = low press. exhaust quality.

$(Q_e - Q_f)\ X_e$ = dry steam to turbine, Q_t.

Table VI and VII

X_t = quality of steam to turbine after passing separator.

$1 - X_t = W$, wetness of steam to turbine after passing separator.

K_e = engine kilowatt output.

K_t = turbine kilowatt output.

Q_e = dry steam to unit per hr.

$\frac{Q_e}{K_e + K_t}$ = actual water rate W for unit.

Q_f = trap water per hr.

Q_s = separator water per hr.

X_1 = high press. quality.

$$\frac{Q_e}{X_1} - Q_s - Q = Q_t'$$

$$Q_t'\ X_t = Q_t$$

$\frac{Q_t}{K_t}$ = actual turbine water rate, W_t

$\frac{Q_e}{K_e}$ = actual engine water rate, W_e

$\frac{Q_e}{K_e + K_t\ (1 + W)}$ = unit water rate, corrected for moisture in turbine steam, W'

$W' - (28.5 - p'_3) = W''$ total corrected unit water rate.

p'_3 = actual vacuum obtained, in mercury.

Tables IX and X.

All throttling calorimeters.

$$X_1 = \frac{H_2 + K\ (T - t_2) - Q}{L}$$

H_2 = total heat per lb. saturated steam at p_2, calorimeter discharge press.

X_1 = quality.

K = separator heat superheated steam at p_2, T.

T = temperature superheated steam in calorimeter.

All separating calorimeters.

$X_2 = \frac{W_f}{W_m + W_f}$

t_2 = temperature saturated steam at p_2.
Q = heat per lb. of the liquid.
L = latent heat vaporization per lb. at p_1.
W_m = moisture.
W_f = flow.

All combination separator-throttle calorimeters.

$X_1 X_2 = X_1$ combined quality.

Thomas electric calorimeter.

$$\frac{\frac{3.412E}{W} - K\,(T-t)}{L} = 1 - X$$

E = watt-hr. input.
W = lb. steam flow.
K = as above.
T = as above
t = saturated steam temperature at p.
L = latent heat per lb. at p.
X = as above.

Table XII, see VI, VII.
Tables XIII, XIV.

$E_t = \frac{\text{kw. } 3412}{H_1}$ for engine turbine or unit.

$E_t' = \frac{\text{kw. } 3412}{H_1 - Q}$ for unit and turbine only.

E_t = thermal efficiency no heat recovered.
E_t' = thermal efficiency hot well heat recovered.

DISCUSSION ON "TEST OF A 15,000-KW. STEAM-ENGINE-TURBINE UNIT", NEW YORK, MARCH 8, 1910

W. L. R. Emmet: While some few applications of low-pressure turbines in connection with electric-generating engines have been put into operation before that which is described in this paper, such cases are relatively unimportant and I think that in all of them the application has been made to a station which was formerly operated non-condensing.

In recent years the science of steam engineering has advanced very rapidly and as the cost of fuel has increased the cost of apparatus has diminished so that we now find ourselves in a position where the question of investment is of much less relative importance than formerly, the value of the product being so very large in proportion to the cost of the apparatus required. For this reason we generally cannot afford to use any apparatus but the best, no matter how great its cost.

The operation of stations by turbines alone is simpler and generally more economical than that of stations which use reciprocating engines and there are many cases where it might be better to install high-pressure turbines instead of coupling low-pressure turbines with existing reciprocating engines. The results shown by Mr. Stott's paper, however, should demonstrate to many station managers that they cannot afford to run reciprocating engines alone when such an improvement can be accomplished by the addition of low-pressure turbines. I regret that Mr. Stott has not dwelt at more length upon the saving in investment and operation which has been effected by this installation, although his tests and explanations afford most of the data necessary for such comparisons. The increase of firing capacity due to the changes made in many of the boilers sometime ago has greatly contributed to the comparisons of the remarkable improvement accomplished. Comparisons of the original conditions in this plant with the ultimate development of the present plan afford a very striking example of what can sometimes be done with an old station.

The results in steam consumption shown by Mr. Stott's tests are very decidedly better than the best results which have ever been accomplished with turbines alone, the advantage in water rate amounting to about 2 lb. per kw-hr. as compared with the best turbine results. It is possible that this station will never produce power more cheaply than the best modern turbine stations are now doing with equal fuel, but the difference cannot be great and when the enormous investment saving is considered, the great value of this change will be apparent.

Some of these curves given in the paper would seem to indicate that the results accomplished by the turbines were inferior to those guaranteed or expected, whereas in fact all guarantees and expectations have been rather exceeded. The reason for this apparent discrepancy is that Mr. Stott has not made allowance for the losses introduced by the presence of moisture in steam entering the turbines, whereas the guarantees on the turbines were based upon dry steam. Mr. Stott has reported the facts as they exist and as they are influenced by such methods of moisture separation as he has used. If the separation were more perfect the turbine results as shown by the curves would be much better and it is probable that with more experience, an almost complete absence of moisture in the steam turbine can be provided for. In Schenectady, where we are operating two large low-pressure turbines on exhaust steam from a reciprocating engine plant, we are running with steam which is almost completely dry. The reason for this is that the steam has to pass horizontally through a long pipe which ends in a separator and is drained before it reaches the separator. This arrangement gives the steam ample time to throw down its moisture and the last vestige of it is taken by the separator. In most applications of low-pressure turbines and engines, such an arrangement can be provided for, while in the installation referred to in this paper the delivery of steam from engine to turbine is in a downward direction and through very short pipes in which little separation or collection of moisture into drops can occur.

Max Rotter: The success of an enterprise of such magnitude and novelty required, on the part of those responsible for it, a very considerable courage and confidence in engineering calculations. The test results and Mr. Stott's deduction from them will exercise no small influence on all who are interested in the production of power on a larger scale.

One matter of practical interest is the elimination of the moisture and oil from the steam during its passage from the engine exhaust to the turbine inlet. Tests 45 to 62 seem to show that the moisture remaining in the steam, as it entered the turbine, amounted to an average of over 4 per cent. Can it be assumed that this may, without re-heating or increased pressure drop, be reduced to zero. If not, then the inefficiency of the separation must be considered as one of the losses inevitable in an installation of this kind, and corrections for moisture entering the turbine should properly be omitted, as such losses would be on a par with the losses in the low-pressure stages of a high-pressure turbine, due to the water of liquefaction delivered to them from the high-pressure stages. It is not the same as a correction for moisture in the steam as originally delivered to the engine, for the engine and low-pressure turbine, with their necessary connecting elements, must be considered as a single unit and it is proper to correct only for conditions due to the imperfection of external apparatus serving the unit. For instance, while a correction for moisture in the steam would be made in testing an engine as a unital piece of apparatus, no such correction would be made in testing, as a unit, the complete plant of such engine and its boilers. The correction of 1 per cent in consumption per 1 per cent of moisture delivered to the turbine is the usual full allowance for the internal losses caused by such moisture; as obviously no deduction of the moisture itself can be made, this having been already allowed for in determining the dry steam delivered to the engine. This correction of 1 per cent is thus equivalent to the customary correction of 2 per cent in consumption per 1 per cent of moisture, as applied to a high-pressure turbine performance. The elimination of oil is probably more important as affecting the maintenance of the efficiency of the turbine and surface condenser than that of the boilers.

One of the most interesting features of the paper is the comparison of this engine and low-pressure turbine installation with an installation of high-pressure turbines. It is not clear whether the high-pressure turbine referred to by Mr. Stott is one of a capacity equivalent to that of the low-pressure turbine only, or to that of the combined engine and low-pressure turbine unit. The latter would certainly be proper and seems to be that considered by Mr. Stott in his statements regarding relative costs; but the high-pressure turbine efficiencies shown in Fig. 19*a*, Series E and F, are apparently those of a considerably smaller machine. Nor is it quite proper to compare the efficiencies of two units on the basis of the test performance of one as against the guaranteed efficiencies of the other. A business man will not guarantee more than necessary, nor will he guarantee under any circumstances the best he can hope to do under test. Furthermore, a slight change in operating conditions might materially affect such a comparison. For instance, the majority of modern high-pressure turbine plants operate with some superheat, of which the high-pressure turbine can take greater advantage than can the engine and low-pressure turbine unit. The frequency of the turbo-alternator, in so far as it determines the speed of the turbine, will also exercise some influence upon the results. At 59th Street the slow speed of 750 rev. per min. is somewhat unfavorable to the turbine. A higher turbine speed would, in the case of the engine and low-pressure turbine unit, increase the efficiency of the turbine only; that is, the improvement in efficiency would apply to only about one-half of the total load of the unit; whereas, in the case of a high-pressure turbine of a capacity equivalent to that of the combined unit, the improvement in efficiency would apply to the full output of the machine. The comparative operating expenses must also be considered, and these are unquestionably lower for the high-pressure turbine than for the combined unit.

For the purpose of comparing the steam consumptions of the two types of apparatus, the final results gvien in Table 12, Series E and F, have been replotted herewith on Fig. 1 and curve A drawn through the points. This curve therefore shows the steam consumption of the combined unit, corrected to dry saturated steam at the engine throttle at 180 lb. gage, dry saturated steam at the low-pressure turbine throttle at variable pressure, and a vacuum equivalent to 28½ in. referred to a 29.92-in. barometer. Curve B refers to a high-pressure turbine unit operating with dry saturated steam at 180 lb. gage and a vacuum of 28½ in. referred to a 29.92-in. barometer, at a speed of 750 rev. per min., and having a capacity about equivalent to that of the combined engine-low-pressure-turbine unit. This latter curve shows the steam consumptions it would be perfectly safe to expect from such unit under test, and it is probable that a consumption 0.3 to 0.4 of a pound lower would be attained. In making guarantees, from 1 to 1½ lb. per kw-hr. would be added. A comparison of these curves would indicate that the average difference of 8 per cent as given by Mr. Stott is ample, and 13 per cent as given by him too high.

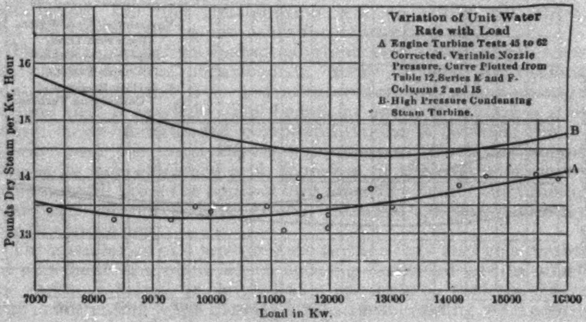


FIG. 1.—Results in Table 12, series E and F

To indicate the effect of a change in operating conditions, curves A and B (Fig. 2 herewith) have been plotted to show the performance of the units when operating under the conditions above mentioned, except that the steam is superheated 100 deg. fahr. It will be noted that the advantage of the combination as against the single unit is materially lowered.

That the high-pressure turbine consumptions, as shown by the curves, are reasonable is proved by a recent unassailable test of this type of turbine, with steam at 180 lb. gage, superheated 100 deg. fahr., and a vacuum of 28¼ in. referred to a 29.92-in. barometer, which showed a consumption of 14.02 lb. per kw-hr.; the turbine having a normal capacity of only 4000 kw. at 1800 rev. per min.

An improvement in efficiency of 13 per cent in the 59th Street plant would almost seem to warrant a combined engine and low-pressure turbine unit as an initial installation, and it would be interesting to learn whether Mr. Stott would consider such an installation for extensions of this plant beyond the capacity obtainable by adding low-pressure turbines to all of the existing engines.

The conditions for which low-pressure turbines are being considered have multiplied much faster than anticipated. For instance it has been proposed to operate a turbine by means of steam from natural geysers, which is perfectly feasible. The steam would be obtained by passing the hot water through vessels in which a pressure drop would take place and part of the water be evaporated. With such an arrangement it would be necessary to handle 30 to 50 lb. of water to obtain 1 lb. of steam at a pressure slightly below atmosphere.

Another use for low-pressure turbines is that of generating power from hitherto wasted industrial steam. For instance, a turbine is now being installed in an automobile tire factory where the retorts used for vulcanizing are filled with high-pressure steam for a certain period, the major portion of this steam being then blown out into the air before the retorts are opened for recharging. This steam will henceforth be collected in a receiver, in which its pressure will drop approximately to atmospheric, and from which it will be delivered to a low-pressure turbine for use. The supply of steam is almost constant and will generate 1000 to 1200 kw., the only cost being the fixed charges, labor, and the water required for condensing.

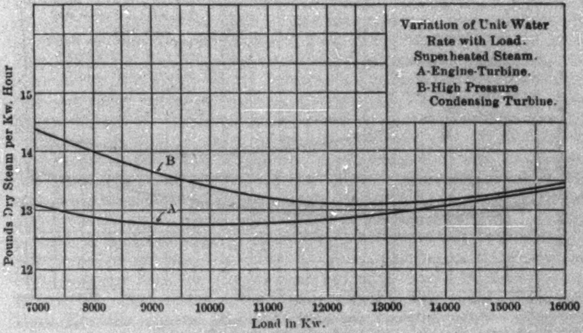


FIG. 2.—Curves A and B, showing performances of units when operating under given conditions

Every improved method or appliance is exposed to the danger of being retarded in the progress it really merits by a few ill-advised applications, and there are conditions under which it would be better not to advocate low-pressure turbines as additions to reciprocating engines. In almost all instances figures will show a saving of steam as achievable by such combination, but the cost of power production in a great many industrial plants is so small an item compared with the other expenses, that a reduction of even 25 per cent in fuel consumption is frequently insignificant when weighed against other considerations.

A low-pressure turbine should not be installed where its steam supply depends upon an old and unreliably decrepit engine. The proper thing here is an independent high-pressure condensing turbine. And as a high-pressure condensing turbine of the same capacity as the engine and low-pressure turbine combined will give so nearly the same efficiency as the combination, the boilers and the condensing apparatus will cost about the same for either installation, the fuel consumption will be about the same, and the engine can be set aside for emergency use.

There are numerous instances where compound engines are not overloaded but underloaded. Many of them are running non-condensing and it is a condenser and not a low-pressure turbine that is needed. The beneficial effect of adding a condenser to an underloaded compound engine is twofold; firstly, it will lower the mean effective pressure at which the engine attains its best efficiency and, therefore, if the engine is underloaded, it will bring the point of best efficiency nearer the running load; and secondly, there is the increased efficiency directly due to condensing.

The installation of a low-pressure turbine may also be a doubtful expedient in a plant which is being electrified and in which the engine is belted or coupled to a lineshaft so that the direct load is decreasing while the electric load is increasing. Of course a generator could be added to the engine, and a low-pressure turbine run in connection with this; but beyond the combined capacity of these it would become absolutely necessary to install a new unit. Under such circumstances the best course would be the installation of a high pressure condensing turbine to start with.

E. F. Miller: I recently made some calculations upon the economy of the low-pressure turbine and found in figuring over some of the tests quoted an apparent efficiency of 76 to 80 per cent of that obtained from the non-conducting engine. I also worked up the efficiencies and steam consumption of the Rankine engine using dry steam at a pressure of 15.6 lb. and exhausting at 28-in. vacuum. The same calculations were made at other pressures down to about 6 lb., as shown in Table 1. Taking the efficiency of the generator as 83 per cent and the mechanical efficiency of the engine as 90 per cent, the steam consumption per kw-hr. was obtained.

Assuming the ratio of efficiency of the low-pressure turbine to that of the non-conducting engine as 63, 67.5 and 72 per cent, the steam consumptions per kw-hr. were calculated. Table 1 affords a simple means by which steam consumptions may be compared.

TABLE 1 STEAM CONSUMPTIONS OF LOW-PRESSURE TURBINES AT VARYING PRESSURES

Abs. press. at entrance	Temp. at entrance deg. fahr.	Abs. press. at exit	Temp. at exit deg. fahr.	Quality of steam at entrance	Quality of steam at exit	Thermal Eff. of Non-cond. eng. %	Steam per h.p.-hr. of non-cond. eng. per cent	Steam per kw-hr. of non-cond. eng. calling mechanical eff. of eng. 90 per cent and eff. of generator 93 per cent	Steam consumption per kw-hr. of low-press. turbine assuming ratio of act. eff. to that of non-conducting eng. as 63, 67.5 and 72 per cent		
15.60	215	1.005	102	1.000	0.8785	15.93	14.72	23.55	33.6	31.4	29.4
14.13	210	1.005	102	1.000	0.8827	15.38	15.23	24.36	34.8	32.5	30.4
11.53	200	1.005	102	1.000	0.8916	14.23	16.50	26.40	37.7	35.2	33.0
9.34	190	1.005	102	1.000	0.9007	13.03	18.09	28.94	40.1	38.6	36.2
7.51	180	1.005	102	1.000	0.9125	11.75	20.13	32.20	46.0	42.9	40.3
5.99	170	1.005	102	1.000	0.9203	10.48	32.66	36.26	51.8	48.3	45.3

Edward L. Clark: A number of cases have arisen where mills driven mechanically have desired to increase their power by the use of low-pressure turbines. The introduction of the low-pressure turbine in such places is accomplished in a novel and effective manner by tying the electric load and the mechanical load together by means of a synchronous motor or generator. The synchronous motor may either be belted or coupled-direct to the main line shaft driven by the engine, and then electrically interlocked with the generator connected with the low-pressure turbine. With this method, the low-pressure turbine requires no governor and merely delivers power in proportion to the quantity of steam exhausted by the engine.

It is important in the selection of a low-pressure turbine that it should be capable of utilizing the entire engine exhaust. In this arrangement, the turbine may be regarded as the low-pressure cylinder of a triple-expansion engine, and manifestly a proper ratio between the low-pressure turbine and engine cylinders should be chosen. If this feature is not observed, the expansion of the steam will not be efficiently carried out or there will be free escape of a part of the steam through the relief valve between the engine and turbine. However, a properly selected turbine will pick up the electrical load and the surplus power that it is delivering will go through the synchronous motor, thereby lightening the load of the engine. When the engine is thus relieved of a portion of its load, it naturally gives less steam to the turbine until the whole system automatically balances between the mechanical load and the electric load.

An important feature of operating the low-pressure turbine without a governor is that vacuum comes back on the engine at all loads, the amount of this vacuum being proportional to the amount of load carried by the turbine. By thus varying the inlet pressures on the turbine and maintaining them below atmospheric pressure, looping of the low-pressure card on the engine at light loads is avoided and the low-pressure valves operate smoothly and without noise at all loads. At the same time, both the engine and turbine run in combination at maximum efficiency through their entire range, and the curves obtained are about as straight as the one in Mr. Stott's test.

It will be seen that the flexibility of such an outfit is independent of the mechanical load and the turbine can accomplish practically anything that a high-pressure turbine can accomplish. The gain in power with the synchronous motor system amounts to nearly 100 per cent, due to the fact that the increased rating of the non-condensing engine over what it is at best economy condensing is approximately 20 per cent, which should be added to the 80 per cent additional power given by the low-pressure turbine.

Assuming that an engine running under 125 to 130 lb. pressure consumes per indicated horse power 15 lb. steam-condensing and 21 lb. non-condensing, if we divide the additional steam required when running non-condensing by the kilowatts obtained from a low-pressure turbine, we obtain a kilowatt for very close to 12 lb. additional steam per kw-hr. This must compare with a water rate of say 20 lb. on a high-pressure turbine under the same steam conditions.

An interesting point is that the economies obtained for the combined engine and turbine would be equivalent to a consumption of about 11 to 11½ lb. per indicated horse power in steam engine practice, so that we better the engine economy over what it is at its best point when run condensing, besides producing a kilowatt for less steam than in a high-pressure unit.

In the majority of cases the low-pressure turbines have been installed in plants having from 125 to 140 lb. of steam, and the relative gain is just as marked as in the stations carrying 195 lb. of steam and high degrees of superheat.

E. D. Dreyfus: It is interesting to note the remarkable difference in Rankine cycle efficiency between the engines and the low-pressure turbines. This looks as if there is some opportunity for improvement on the low-pressure turbine. Mr. Flanders of East Pittsburg, has made quite a study of turbine efficiencies, and has found that a high-pressure complete expansion turbine operating with 175-lb. steam pressure and 100-deg. superheat will give the same Rankine cycle efficiency as a low-pressure turbine at the same vacuum and using dry saturated steam.

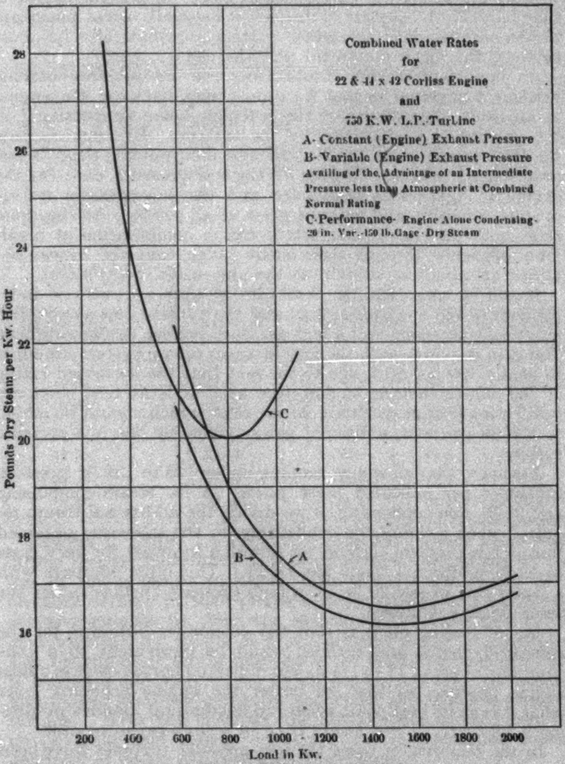


FIG. 1

The gain in economy of 13 per cent, as stated by Mr. Stott, is what would be expected when we consider that this unit is operating on dry and saturated steam. I must, therefore, differ with Mr. Rotter, as I know of no complete expansion economies on record that do not agree to a large extent with what Mr. Stott has brought out. A Rankine cycle efficiency of 70½ per cent on a complete expansion machine, but no turbine performance reaching this degree of efficiency has to my knowledge been recorded in this country. Some have gone as high as 67.8 per cent, but as far as I am able to learn, any record of a complete expansion machine that has exceeded 70 per cent is within closed doors.

I am very much interested in observing the results obtained with constant and variable exhaust pressure. When this question first came up in low-pressure turbine work, variable exhaust pressure was looked upon with disfavor by some designers and engineers, while others advocated this method because of the better results obtained with it. It is now quite evident that in the neighborhood of 5 per cent additional economy is obtained by running with variable exhaust pressure. As Mr. Stott has stated, it is obvious that unless the piping and apparatus between the engine and turbine are in very good condition, good vacuum will not obtain. I find, however, that there are a number of low-pressure turbine installations where the low-pressure turbine is coupled with two or more compound Corliss engines with moderately long connections, and they secure a vacuum in the neighborhood of 28½ or 29 in. The overall economy, even in the small 1000-kw. unit, indicates the same relative gain as shown by Mr. Stott's results. Fig. 6 and Fig. 7 in Mr. Stott's paper, show the desirability of variable pressure operation on account of looping of the cards.

Mr. Stott mentioned in the first part of his paper that the maintenance account of a complete gas-engine plant would be from four to ten times that of a turbine station. To the best of our ability in collecting information and judging working conditions, we do not find it comes up to this factor, and the same thing is true in England according to a paper presented before the Institution of Electrical Engineers on November 17, 1908. This paper was very thoroughly discussed at London, Dublin and Manchester, both favorable and adverse comment being made, but the prevailing opinion seemed to be that the maintenance cost of the complete gas plant would not much exceed that of the steam turbine plant; in fact, the author of this paper claimed it to be the same. When the producer and boiler are considered, there is reason for this statement.

Regarding the statement that the results obtained closely approach gas-engine efficiencies, gas-engine coal consumption is usually given for 12,000 to 13,000-B.t.u. coal, but considering 14,500-B.t.u. coal in both steam and gas plants, a material difference of 20 to 25 per cent will easily be obtained in favor of the gas equipment over the most efficient steam machinery.

The value of the low-pressure turbine is rapidly bringing about its extensive use in connection with the gas engine, availing of the waste heat of the jacket and exhaust.

Charles P. Steinmetz: The paper deals with a combination of the low-pressure steam turbine with the induction generator, which, while possibly not familiar to some, is assuming a very high industrial importance.

The electrical part of the unit, the induction generator, is not a new type of machine. Its existence was known and its characteristics and behavior investigated and discussed many years ago; but only now has the industry developed in such a manner as to give conditions in which the induction generator is preferable to the synchronous generator.

There are two kinds of alternating-current generators: the synchronous generator, which is the ordinary alternating-current machine with which we are familiar, and the induction generator. Constructively, the stator or stationary structure of both types of alternator is practically the same in construction. It comprises a polyphase winding, in which the electromotive force is induced by the rotating magnetic field, arranged in a laminated structure. The difference between the synchronous generator and the induction generator is in the rotor. In the synchronous generator this is a revolving magnetic field excited by direct current; while in the induction generator it contains a short-circuited winding the same as the armature winding of the familiar induction motor. From this variation results the difference in the production of the magnetic field which by its rotation induces electromotive force in the stationary generator winding. The magnetic field of the synchronous generator is produced by the action of the direct current in the field poles; that of the induction generator is produced by the reaction of the alternating currents issuing from the induction generator. As a consequence the synchronous generator must run in step with the frequency of the alternating system; that is, the rotor must move exactly one pole for every reversal of voltage in the external system. Conversely, the induction generator cannot run in step with the frequency but must always run faster, exceeding synchronism by an amount depending upon the load, so as to cause the induction in the short-circuited windings which produces the currents therein. That means that synchronizing is not required in the induction generator. Furthermore, since the induction generator does not depend upon running in step with any other machine, the possibilities of see-sawing, the so-called hunting which may occur in the synchronous machine, cannot exist with the induction generator.

The difference in the production of the magnetic field of the two types of alternating-current generator is the cause of the very characteristic variations in their performance. The magnetic field of the synchronous machine and, therefore, the electromotive force induced in its armature, depends on the direct current supplied to its field winding, but is essentially independent of the load of the machine. It is dependent only in so far as the current output and the power factor modify the field, varying it in the manner expressed by the term " regulation of the machine ". The induction-motor field is produced by the reaction of the currents issuing from the machine. The induction generator, therefore, has no regulation and no magnetic field, independent of the voltage at the terminals and the load, but the magnetic field of the induction machine is produced by the reaction of the currents at a value corresponding to the voltage produced at the induction-generator terminals by the synchronous machines connected to the same system. The induction generator depends in its magnetic field and voltage on the excitation of the synchronous machines in the same system; that is, it can generate only when connected to a system to which synchronous machines are also connected, whether synchronous generators, motors, converters or equivalent apparatus. It has no voltage of its own and cannot operate on a system on which no synchronous machine is connected.

The regulation of such a combined system of synchronous and induction machines, therefore, is the regulation of the synchronous machines operating on the system. Any change of load varies the voltage as it would be varied if this change of load occurred on the synchronous machines in the system. The induction generator is merely a machine feeding electric power into the system but not participating in the voltage regulation or voltage control and having no direct effect on the voltage. While the synchronous machine at open circuit has a terminal voltage, the induction generator ceases to generate and has no voltage at its terminals at open circuit if it is disconnected from the alternating system. In a synchronous generator, even when short-circuited, the electromotive force continues to be induced in the armature windings because the magnetic field is still there as produced by the direct current. The synchronous generator therefore has a short-circuit current which may be many times full-load current, since the total induced electromotive force must be consumed inside of the synchronous generator armature. An induction generator, when short-circuited, has no voltage at the terminals, and therefore receives no current, has no magnetic field, and ceases to generate. In the induction generator when short-circuited, the current dies down from its previous normal value to zero at a rate depending on the resistance and inductance of the internal circuit in just the same manner as the current in a reactive coil, for instance, would die down when the coil is short-circuited and the impressed voltage withdrawn from it. The short-circuit current of the combined system of synchronous and induction generators is therefore only the short-circuit current of the synchronous generators.

There results therefrom also the characteristic difference that the synchronous generator can generate current of any character, energy, reactive or wattless lagging, or leading, depending on the nature of the system to which it is connected, or the power factor of the supply system; while the induction generator can generate only energy current, and in addition continuously consumes or receives a certain amount of reactive or wattless lagging current required for its excitation. This latter it receives from the synchronous generators or the synchronous motors and converters in the system. The induction generator, therefore, cannot supply alone a general alternating-current system, for instance, a system of light and power distribution, which requires energy current, as well as reactive, or wattless lagging current; and where a combination of synchronous and induction generators is used, all the lagging current of the system must be supplied by the synchronous generators, and in addition the lagging current also consumed by the induction generator for its excitation.

In a system in which there is considerable lagging current, a very large percentage of induction generators is a questionable advantage, since it may throw an excessive overload in current on the synchronous generators, the latter having to supply all the lagging current. On a system requiring no lagging current, or being built to supply lagging current, as rotary converters or synchronous motors, which is the type of system on which Mr. Stott's generators operate and is usual in the large electric power-generating and distributing systems, mainly of 25-cycles, there is no lagging current required because the system can be run at unity power factor or even at leading current, and the synchronous motors and converters can be caused to supply the lagging exciting current of the induction generators. There the induction generator is at its greatest advantage.

The difference may possibly be described by saying the synchronous generator generates electric current while the induction generator generates electric power. That is, the synchronous generator supplies electric current to the system whether this current is a power current or a wattless, powerless current; the induction generator can supply only power current and no wattless current. The induction generator. therefore, is the typical converter from mechanical into electric power. It consumes mechanical power, supplies electric power without depending in its supply on field excitation, speed, synchronism or any other feature. It is consequently the ideal machine to float on an alternating-current system, by receiving whatever mechanical power is available and supplied to it a low-pressure steam turbine from the exhaust steam of reciprocating engines; or in the hydraulic turbine from whatever water power there may be available. It receives the mechanical power and converts it into a proportional amount of electric power, at whatever voltage the system happens to run on, and at any speed, speeding up just above that for which the system is set by its frequency, but with no necessary regulation. Its straight and simple function is the conversion of one kind of energy to the other, separate entirely from the problem of regulation and adjustment which is thrown over into the synchronous machines in the same system. This is what makes the induction generator a simple and convenient apparatus for cases like that described in the paper and for all others where mechanical power is to be picked up from water powers here and there, and is too small, possibly, to warrant installation of specific regulating mechanism.

There is an interesting and somewhat unexpected result shown by the tests, namely that the efficiency was found higher when operating the turbine with varying nozzle pressure than when operating with constant nozzle pressure. The explanation of this is given by the curves in Fig. 13 and Fig. 14. In the latter the efficiency of the low-pressure turbine is higher for constant nozzle pressure, just as expected, but constant nozzle pressure of the turbine means constant exhaust pressure of the steam engine and with this and the varying load, as shown in Fig. 13, the efficiency of the steam engine falls off, dropping from the maximum point at a rate which is so much greater than the gain in efficiency of the steam turbine that the combined efficiency shows an advantage in favor of varying nozzle pressure. This illustrates the fact that the turbine side is much less sensitive to variations of the operating conditions from its best condition than the steam engine is, and that to get maximum economy in the operating conditions the engine should be favored. But that also throws a side-light on one of the reasons why the Rankine efficiency of the turbine is less than that of the steam engine part, because all the unfavorable conditions of operation must be thrown on the turbine side of the cycle to get maximum average resultant efficiency.

The gain in efficiency due to the addition of the low-pressure turbine is on the lower side of the cycle, because of the possibility of extending the expansion below the exhaust pressure of the low-pressure cylinder of the steam engine, an extension impossible with the reciprocating engine. The combined apparatus gains in the ability of the turbine to do what the reciprocating engine is not able to do. This must be kept in mind when comparing the low-pressure turbine and steam-engine plant with the high-pressure turbine plant.

The reciprocating engine in general cannot gain by superheat as much as the steam turbine gains, and comparison of the combined efficiency of a saturated-steam reciprocating engine and low-pressure turbine with a high-pressure turbine is not quite fair to the latter, because on the high-pressure side, the steam turbine can get an additional gain in efficiency by using superheat which the reciprocating engine cannot to the same extent. In comparing things it is always difficult to get conditions which are equally fair to both types of apparatus because the conditions of proper operations are different in each.

J. W. Lieb, Jr.: The author is somewhat optimistic in his estimate that it would be possible to realize as much as 20 per cent of the installation cost from the sale of used apparatus. It would probably be necessary to accept a lower figure, but the result, however, would be still more in favor of the installation of the low-pressure turbines.

In the application of the induction generator we have a solution of the problem which combines simplicity of construction and operation with a minimum of installation cost. The induction generator is also of notable assistance in solving the otherwise very difficult problem of handling through the available types of switching gear the enormous energy which might with the usual types of apparatus be difficult to handle in case of a short circuit on the bus bars.

The results of the condenser tests are particularly interesting on account of the high rates of heat transference, considerably in advance of the results hitherto attained.

The paper is a notable contribution to the economics of power plant engineering and the apparatus described should serve to give a new lease of life to otherwise antiquated engine-driven equipments, although it would be difficult to find another case where the application could be made with such manifest advantages.

D. S. Jacobus: I visited the plant of the Interborough Company while Mr. Stott's tests were being made and desire to commend most highly the degree of accuracy observed and the general character of the work.

The economy of all piston steam-engine installations may not be improved as much as 25 per cent by adding a low-pressure turbine. By examining the paper on tests made at the plant of the Pacific Light and Power Company at Redondo, California, presented to this Society by Mr. Weymouth, it will be found that the heat consumption with a steady load with piston steam engines was about 24,800 B.t.u. per kw-hr. The heat consumption was obtained by dividing the heat of combustion of the oil burned at the boilers by the net electrical output in kilowatt-hours at the switchboard. The efficiency in the tests of the combined unit by Mr. Stott is 20.6 per cent based on the heat in the steam consumed, and if we take the efficiency of the boilers at 76 per cent, a figure obtainable with oil, the heat of combustion of the fuel burned at the boilers would be 21,800 B.t.u. The difference between Mr. Stott's figures and those obtained at the Redondo plant is, therefore, about 12 per cent. There is a further allowance for the fact that the steam was superheated about 100 deg. fahr. in the Redondo tests and this would increase the figure and make it come more than 12 per cent. It does not seem possible that the introduction of a low-pressure steam turbine at the Redondo plant could ever reduce the heat consumption 25 per cent, bringing it down to 18,600 B.t.u. per kw-hr.

The results obtained by Mr. Stott are very close to those which can be secured with large gas engines. The economy of 21,800 B.t.u. could be reduced with proper superheat to about 20,000

B.t.u. per kw-hr., which would be all that could be expected of a producer-gas plant if run on a commercial swinging load with high daily peaks and periods of low power. In a 15 days' continuous test made at the Redondo plant where the load varied daily through a wide range from high peaks to periods where but little load was on the station and where there was a lay-over period of 4½ hours per day, the heat consumption averaged about 25,000 B.t.u. per kw-hr. and it is questionable whether a producer-gas-engine installation could do very much better with a load of this character.

Mr. Schauber: In regard to the statement that the result obtained with the engine-turbine-unit had closely approached the best efficiency obtained in gas-engine practice, I desire to call attention to the installation of four 2000-kw. units at the Illinois Steel Company, operating on blast furnace gas. Records kept for six months under working conditions show a consumption of 15,000 B.t.u. per kw-hr. at the switchboard. When this result is compared with the 21,000 B.t.u. per kw-hr. at the 59th Street station, the comparison is more in favor of the gas engine than the statement made in Mr. Stott's paper.

D. S. Jacobus: The 15,000 B.t.u. quoted by Mr. Schauber is based on the heat of combustion of the blast furnace gas used by the engines. If there had been a producer this value would correspond to that computed on the basis of the low heat value of the gas, and where allowance is made for losses through all auxiliaries, this figure would have to be divided by about 0.7 to give the heat units in the original fuel. This would give a much higher heat consumption, say, over 20,000 B.t.u. per kw-hr.

G. R. Parker: The question often arises as to the smallest size of plant in which a low-pressure turbine can profitably be made, and while no accurate data is yet available, I consider it doubtful if very satisfactory results can be obtained in plants of less than 300 or 400 kw. This is due to the fact that the actual cost of producing power in small installations, is not made up so largely of coal as it is in large installations, the labor and the numerous operating expenses constituting a much larger percentage of the cost.

A word of appreciation is due Mr. Emmet for the persistance with which he has worked on the problems of the turbine industry, through many early trials and difficulties, until his latest and possibly his greatest achievement, which Mr. Stott has so ably presented. I feel confident that engineering posterity will give due credit to Mr. Emmet.

O. Junggren: The over-all efficiency shown by Test 51, Table 8, is 72½ per cent of the total available energy between the steam entering the engine and the recorded exhaust pressure of the turbine. Test 42 shows an efficiency of 69.6 per cent, and another, 68.7 per cent under different conditions of load and vacuum. A high-pressure turbine, working under the same conditions of steam pressure and vacuum, would probably not give as high an efficiency over such an available range of load as that given by the combined unit, but a high-pressure turbine of approximately the same size could reasonably be expected to give 70 to 70½ per cent at the most economical load, although fractional efficiencies would not be as good as for the combined unit. A high-pressure turbine would be considerably cheaper than the combined unit and in the near future high-pressure turbines will be made having as high an efficiency as the combined unit, and still be cheaper than a combination of engine and turbine. The vacuum obtained in these tests are quite remarkable and show what can be done in actual practice.

F. Samuelson said that the field for variable-pressure turbine work, not yet developed in America, has been fully opened up in England and the business is in a very healthful condition. Low-pressure turbines of various types have been employed and all are proving fairly successful. The chief difficulty in the installation of these machines has been to meet the Board of Trade regulations as to constant back pressure on hoisting engines. Accidents are sometimes caused by a drop in back pressure at the engine, due to demands upon the accumulator by the turbine. To prevent this trouble a simple automatic valve has been employed between the engine and the accumulator to shut off the supply from the engine when the accumulator pressure falls to atmospheric. While the regulating valve is closed the turbine is supplied with steam at a reduced pressure. This valve works equally well between the turbine and the accumulator, but the capacity of the latter is much reduced because of the small pressure limit between which it operates. This results in the use of high-pressure steam in the turbine on short stoppage of the engine.

The Authors: Refiguring one of the assumed cards (Card C, Table B) for 100 deg. superheat, we get an actual water rate of 12.9 lb. per h.p. instead of 13.6 with saturated steam, since the missing water and leakage is cut to less than 0.1 of the original value in the high-pressure cylinder. As the missing water in the high-pressure cylinder forms about 0.6 of the total missing water, we shall have 0.46 of the original missing water in this case, or $0.156 \times 0.46 = 0.072$, say roughly 0.08. The B.t.u. supplied per hour = $12.9 \times 9836 \times 1259 = 159{,}800{,}000$. Radiation and conduction, 1 per cent = 1,598,000 B.t.u-hr. High-pressure cylinder work = $5080 \times 2545 = 12{,}940{,}000$ B.t.u-hr.; this leaves 145,262,000 B.t.u. in the steam at high-pressure exhaust, or $\frac{145{,}262{,}000}{126{,}900} = 1145$ B.t.u. per lb. At 52.2 lb. absolute, this corresponds to a quality of 96.8 per cent or 3.2 per cent moisture; of this about 2 per cent will be thrown down as receiver drain.

The heat thus removed is $0.02 \times 126{,}900 \times 253 = 643{,}000$ B.t.u., leaving 144,619,000 B.t.u. in 124,360 lb. of steam, delivered to the low-pressure cylinder. Low-pressure radiation, 0.01 ×144, 619,000 = 1,446,000; low-pressure work = 4756× 2545 = 12,100,000; leaving 131,073,000 B.t.u-hr., or 1065 B.t.u-lb. which at 13.5-lb. absolute exhaust pressure gives a quality of 91.5 per cent, or 113,800 lb. dry steam available for the turbine. This will give 3,700 kw. on the turbine, which added to the 6710 kw. on the engine gives 10,410 kw. at 12.18 lb. per kw-hr. as against 14.2 lb. with saturated steam. In actual practice the 14.2 rate was cut down to 13.25, and it is reasonable to expect the same sort of result under superheat.

The reciprocating engine, when designed for superheat, makes just as good use of it thermodynamically as a steam turbine, but will not stand so much superheat. The point has been raised, that a moisture correction on the turbine is not fair, since without reheating it is not possible to reduce the moisture in the turbine steam to zero. It is fair in this sense, that in order to compare the various water rates on the same basis, it is necessary to reduce all steam conditions to a standard and that standard is naturally dry steam. Moreover, when the moisture gets as low as 1 per cent or 2 per cent the correction is negligible in amount, and the curve of corrected water rate is substantially true. It is quite possible that a separator can be designed that will take out all but 0.2 or 0.3 per cent of moisture; and in this case the correction justifies itself.

H. G. Stott: In reply to the question by Max Rotter as to whether it would be advisable to install in a new plant such a combination as described in the paper, the accompanying diagram (Fig. 1) showing the factors entering into the cost of power, will answer his question. For example, with a low load factor, it is quite evident that the all-important point is to keep down the fixed charges, for when the load factor is less than 20 per cent, the fixed charges are of vastly greater importance than any possible gain of efficiency due to a better type of prime mover. This is true of any plant, and the curve shows the futility of attempting to carry peak loads by means of gas engines, water power or any other prime mover necessitating a large investment per kilowatt. On the other hand, with loads having a load factor of over 60 per cent especially where fuel cost is high, the investment factor is of relatively small importance, and the all-important matter is to keep down the maintenance and operating charges by using the most efficient type of plant obtainable, provided that it is at the same time thoroughly reliable.

The total cost of power can be obtained from these curves by simply taking the sum of the ordinates above and below the axis for any load factor desired.

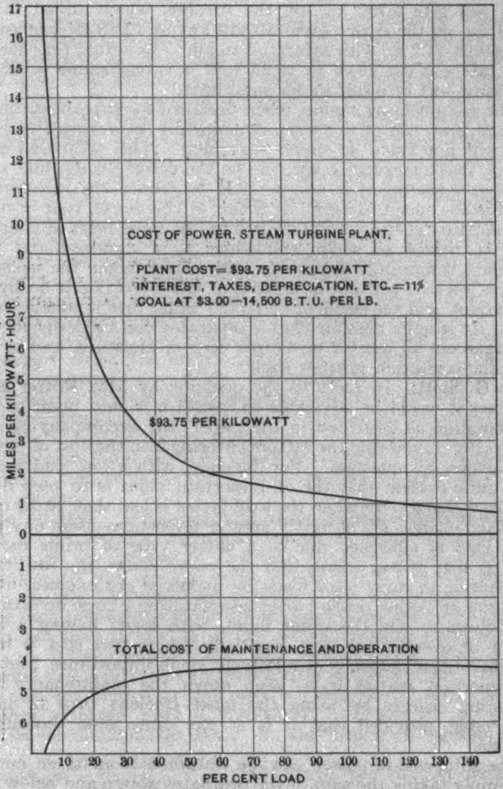


FIG. 1—Diagram of factors entering into the cost of power.

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ELECTRIC MINE HOISTS

BY D. B. RUSHMORE AND K. A. PAULY

Of primary importance in mine installations is the hoist, which has a very direct bearing on the successful operation of a mine. Conditions vary greatly with different mines, and especially in different localities. Such factors as depth, incline, the number of levels, permissible or desirable speeds, conditions of ore, etc., are always more or less special in each case. Veins of ore are never exactly duplicated, and the nature of the ground through which shafts are sunk may considerably modify permissible values. As mining laws are made by the different states they necessarily vary somewhat, and, even when not fully observed, they introduce factors which qualify the conditions of hoisting men and ore. The amount of timbering required is often of importance as relating to hoisting conditions. Methods of loading ore affect the time required, as also does the question of the use of cars or skips. Safety precautions must be very carefully considered, and the number of men in each mine, the number of compartments, and often the method of removing water from the mine must have careful consideration.

While a general discussion of the subject of hoisting is possible, most cases are entirely special and can be considered only in connection with the peculiar conditions pertaining to that particular installation.

The cost of installation of the hoisting plant may be an appreciable amount, while the cost of raising the ore may be but a small part of the total operating charge. In many cases, however, the output of the mine is limited by the capacity of the hoist, and the latter thus becomes of the first importance. Where shafts have not been sunk to their final depths the conditions of operation are of necessity constantly changing, and it is impossible to predetermine with exactness the precise conditions of operation which will be followed in practice.

Power for Mines. Power is used for drilling, tramming, pumping, ventilating, hoisting, compressing air, crushing rock and for many minor operations. In coal mines, the washeries and breakers, and in metal mines, the mills and concentrators, are ordinarily located in proximity to the shafts. The problem of lighting always exists.

Owing to the distances between different points of applications of power, not only the question of utilization but also that of transmission becomes of importance. Three forms of power, steam, compressed air and electricity, are to be considered. Originally, of course, the power must come from coal or water power.

Choice of System. The choice of the best system of hoisting in any particular case is the result of considering carefully many different factors. Most important among these is the cost of operation and installation. In this regard the location of the power house to ensure the best and cheapest supply of fuel and water is of primary importance. It is highly desirable to group a large number of mines, so that they may be supplied from one power station. As a rule, mining shafts are not well-situated as regards the supply of coal and water, so that it is usually necessary to transmit power for some distance, and this is best done by electricity. The problem then becomes one of the utilization of power, or the generation of electricity by means of steam turbines or gas engines. In metal mining, fuel is usually expensive and often but little water is available at the mines, so steam hoisting engines are generally run non-condensing. Where the reverse is the case, it is in most cases cheaper to transmit electricity to the mines than to pump condensing water there.

Efficiency of Steam Plants. Steam hoisting plants are known to be very inefficient, but the exact figures are usually difficult to obtain. With non-condensing engines and an extremely intermittent load on both engines and boilers, the economy necessarily is very poor. Steam engines must be designed for starting conditions, where they take steam under full stroke, and this necessitates their running with an early cut-off when hoisting. With a number of plants close together, there is no way of returning power to the line or of smoothing the peaks of the load. It is impossible, when a steam engine is used, to store power in retardation. There is also a limit in the depth at which steam engines can be satisfactorily placed, and their installation in mines is thus very undesirable.

Advantages of the Electric System. In many cases the electric system of hoisting has advantages which give it decided preference. The power house may have the most favorable location —power may be taken from some existing transmission system, or a water power may be developed for the purpose. Power may be centrally generated at the highest efficiency, and distributed over a large area. Electricity is most easily applied to all work on both the surface and the interior of mines. One of its greatest advantages in practice is the ease of making extensions to the development. With one station and many individual loads, an overlapping of peaks occurs, and a consequent reduction in boiler and generating capacity is effected. The cost of installation and operation is much reduced, a much improved load factor results and fewer operators are required.

For underground pumping and tramming, and where the hoists are located in the mine, electricity has every advantage. For use with electric hoists, safety devices have been developed which prevent over-winding and which also limit the acceleration. Power can be returned to the system in braking and in lowering unbalanced, and a much higher fuel economy can be obtained.

The use of hoists operated by compressed air has long been considered and at present some installations are being made. With the usual features of such equipment it is necessary to cool the air during compression and to re-heat it before use. In general, serious questions would arise concerning the efficiency of any system using compressed air for hoisting. The efficiency of an electric hoisting system is not open to question, and can be figured with exactness. There is no reason why advocates of compressed air systems should not be required to give the same guarantees and to state positively just what efficiency they are sure of obtaining.

MOTOR CHARACTERISTICS

Large electric mine hoists are almost universally driven either by shunt-wound direct-current motors or polyphase induction motors, the characteristics of which especially adapt them to meet the peculiar conditions imposed. While in many of their characteristics these two types of motor are similar, they differ widely in others, which are of more or less importance depending upon special conditions of individual cases.

Fig. 1 gives the efficiencies, currents and speeds of the direct-current shunt motor at various loads for constant impressed voltage, and Fig. 2 gives similar curves for the induction motor, to which is added the power-factor curve. By reference to these curves it will be seen that the free-running speed of each motor is limited, and that the variations in speed with changes in load are small; that each becomes a generator when driven above speed, and may therefore be used as a brake when lowering unbalanced loads, returning power to the supply system; that the efficiencies of both when operating either as motor or generator are virtually the same for corresponding loads.

The speed of the shunt motor for a given load may be varied between standstill and full speed either by changing the potential of the supply system, or by inserting resistance in series with its armature. However, because of the inefficiency of this latter method of control, it is seldom, if ever, used in connection with large hoist motors. The only practical method of obtaining a similar variation in the speed of an induction motor is by changing the amount of resistance connected in its armature circuit. Fig. 3 shows the efficiencies of the shunt motor at various speeds when exerting full-load torque, the variations in speed being obtained by voltage control, and the efficiencies of the induction motor being under similar conditions, except that in this case the variations in speed are obtained by armature rheostatic control. By reference to the curves it will be seen that for a given torque, the efficiency curve of the shunt motor at reduced speeds resembles that for the constant speed motor at reduced loads, while the efficiency curve of the induction motor is a straight line between full-load efficiency and speed, and zero efficiency and speed. From this it follows that, for a given value of torque, the input to the shunt motor at reduced speeds, except for very low speeds, is approximately proportional to the speed, while the input to the induction motor is constant and independent of the speed. It will also be noted that the shunt motor may be driven as a generator at reduced speeds, while the induction motor can be made to generate only when driven above synchronous speed. Where the conditions are such that it is desirable to drive the hoist at reduced speeds for any considerable lengths of time, the efficiency of the induction motor drive may be improved by using a motor designed for two speeds,

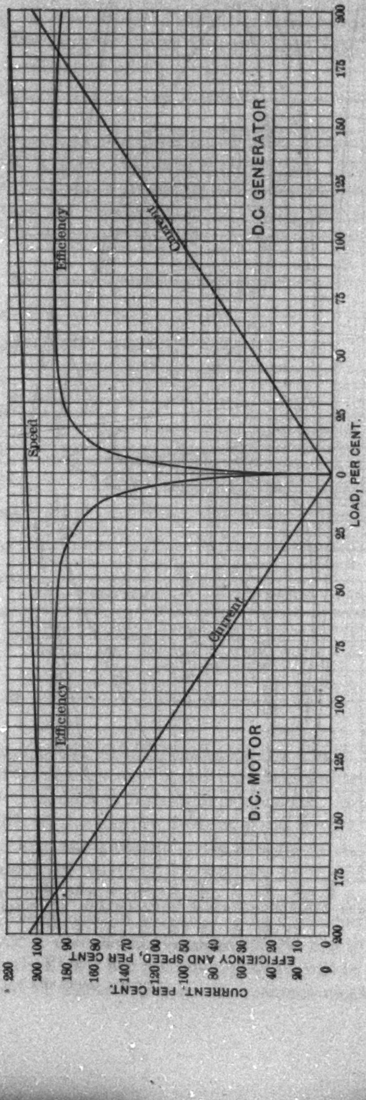
D.C. GENERATOR
D.C. MOTOR
Speed
Efficiency
Efficiency
Current
Current
LOAD, PER CENT.
200
175
150
125
100
75
50
25
0
25
50
75
100
125
150
175
200
EFFICIENCY AND SPEED, PER CENT
0
10
20
30
40
50
60
70
80
90
100
CURRENT, PER CENT.
0
20
40
60
80
100
120
140
160
180
200
220

FIG. 1

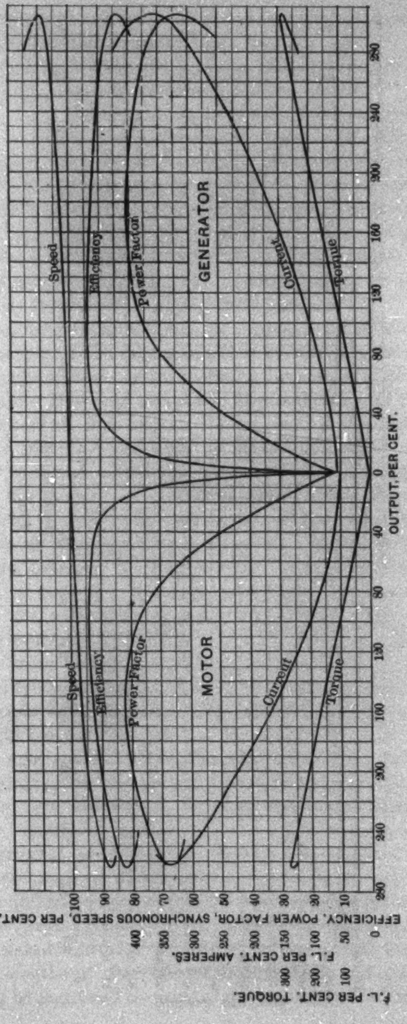
Speed
Efficiency
Power Factor
GENERATOR
Current
Torque
Speed
Efficiency
Power Factor
MOTOR
Current
Torque
280
240
200
160
120
80
40
0
40
80
120
160
200
240
280
OUTPUT, PER CENT.
100
90
80
70
60
50
40
30
20
10
EFFICIENCY, POWER FACTOR, SYNCHRONOUS SPEED, PER CENT.
400
350
300
250
200
150
100
50
0
F.L. PER CENT. AMPERES.
300
200
100
F.L. PER CENT. TORQUE.

FIG. 2

or by using a concatenated set, but the advantages gained are seldom sufficient to offset the increased first cost and the necessary complication of the control.

The number of poles, and therefore the diameter of an induction motor, is determined by its speed and the frequency of the supply system, the number of poles varying inversely as the speed for a given frequency, while the frequency of the e.m.f. generated in the armature of a direct-current motor is independent of the supply system. While this is of little importance in the designing of motors of moderate speed for gearing, it permits of a better proportioning of the length and diameter of shunt motors of very slow speed than is possible in the case of similar induction motors for direct connection, especially where the frequency of the supply system is 60 cycles.

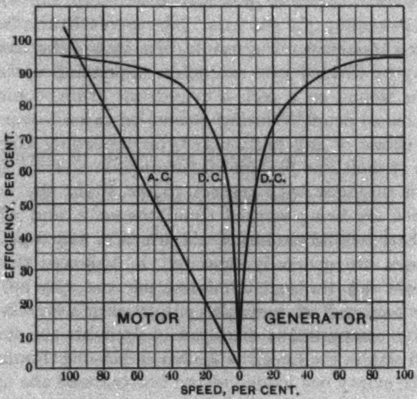

FIG. 3

As pointed out, the efficient speed control of the shunt motor is only obtained by varying the voltage of the supply system, the usual method being to provide a generator for each motor and varying the generated potential. As mine shafts are usually scattered over a considerable area, and the conditions in close proximity to the shafts are not such as to permit of the economical generation of electric power, the central electric station is usually placed at a considerable distance from the hoists, the power is generated and transmitted to the mines as alternating current and is then transformed at each shaft into direct current by motor-generator sets. The losses caused therein must be charged against the shunt motor when comparing its efficiency with that of the induction motor, which may be connected either directly or through highly efficient static transformers with the alternating-current distributing system. The torque and current for the two types of motor are approximately proportional within their operating limits.

Hoist Load Diagrams

Before discussing the various systems of electric hoisting it will be well to consider the nature of a mine-hoist load. Mine hoists may be divided into six types, depending upon whether the rope is wound on a reel, a cylindrical drum, conical drum, cylindro-conical drum, Whiting drums, or carried over a Koepe disk, the choice of any particular type depending largely upon the depth of shaft, the maximum permissible hoisting speed, the location of the hoist with respect to the shaft, the number of levels which are being worked simultaneously, and whether or not the shaft conditions permit the use of a tail rope.

The hoists are generally operated in balance, that is, the weight of the skip (or cage and car as the case may be) carrying the ore, is balanced by a similar empty skip which is lowered in a second compartment simultaneously with the hoisting of the loaded skip in the first, the loaded skip being dumped at the top and the empty one loaded at the bottom, and the cycle then repeated. To permit of adjustment of the length of the ropes for hoisting from different levels, it is customary to use two reels or drums mounted on the same shaft, one being keyed to the shaft and the other being driven by it through some form of clutch. The length of rope on the Koepe disk hoist or the Whiting hoist cannot conveniently be adjusted for different levels except within very small limits.

For the purpose of comparing the load diagrams of the different types, each hoist is assumed to lift 8000 lb. of ore in a skip weighing 5000 lb., from a vertical depth of 2500 ft. at an average speed of 2000 ft. per min., allowing 20 sec. for acceleration and 15 sec. for retardation. The rope for the reel hoist is assumed to be 5 inches x ½ inch, weighing 4½ lb. per ft. and that for the others 1⅜ inches round steel rope weighing 3 lb. per ft.

Reel Hoist. As its name indicates, the reel hoist consists of two large reels on which the rope supporting the skips is wound in a spiral, the distance between the flanges of the reels being approximately equal to the width of the flat rope used. The reel hoist is generally used where it is necessary to place the hoist very close to the shaft. As the minimum diameter of the reel, usually from 5 to 8 ft., is limited, and as its maximum diameter is determined by the thickness and length of the rope, the depth from which hoisting may be done at a given average speed by reel hoists is governed by the maximum permissible hoisting speed.

Let us assume that the loaded skip is at the bottom of the shaft and that the empty skip is at the top. Then the length L_a of the ascending rope with the skip at any point in the shaft may be obtained from the equation

$$L_a = D - 2\,\pi\,a\,r_1 - \pi\,a^2\,b$$

and its moment, M, about the drum shaft by

$$M_1 = (D - 2\,a\,\pi\,r_1 - \pi\,a^2\,b)\;r\,n\cos\phi$$

in which D = depth of shaft; b = thickness of the rope; n = the weight of the rope per foot; r_1 = the radius of the rope on the reel when the skip is at the bottom of the shaft; a = the number of turns of the reel in raising the skip from the bottom of the shaft to the point in question; $r = r_1 + a\,b$ = the radius of the rope on the reel after a turns and ϕ = the angle which the shaft makes with the vertical.

The moment of the ascending load is obtained from the equation:

$$M_2 = (W_1 + W_2)\;r\cos\phi$$

where W_1 = the weight of the skip (or cage and car as the case may be) and W_2 = the weight of the ore.

Plotting M_1 and M_2 against revolutions of the reel, we obtain curves M_1 and M_2 in Fig. 4.

The moments M_1' of the descending rope may be plotted from the values obtained for the ascending rope, by simply assuming the center of coördinates in Fig. 4 transferred from the left to the right side of the curves, turn No. 10 of the descending load corresponding to turn No. 81 of the ascending load, etc.

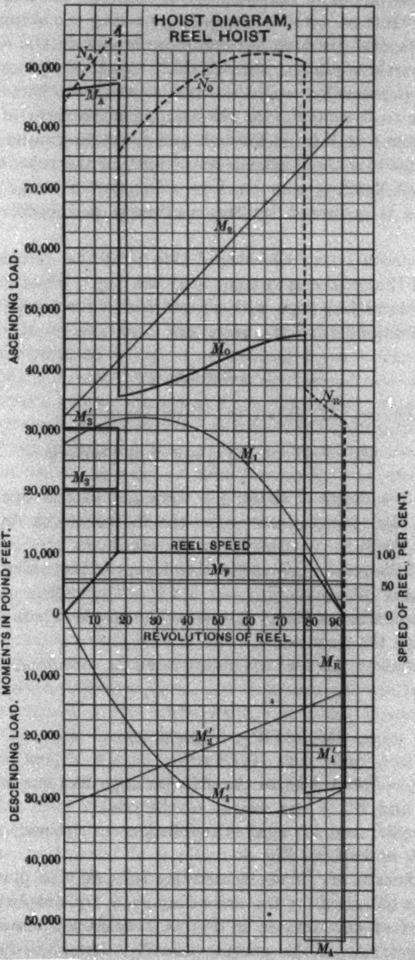
HOIST DIAGRAM, REEL HOIST
ASCENDING LOAD.
DESCENDING LOAD.
MOMENTS IN POUND FEET.
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
10,000
20,000
30,000
40,000
50,000
N_A
M_A
N_0
M_2
M_0
N_R
M_3'
M_3
M_1
REEL SPEED
M_F
10
20
30
40
50
60
70
80
90
REVOLUTIONS OF REEL
M_R
M_2'
M_1'
M_1'
M_4
100
50
0
SPEED OF REEL, PER CENT.

FIG. 4

Similarly, the moment M_2' of the descending load may be obtained by substituting W_1' for W_1+W_2 in the equation for M_2, and plotting as directed for the descending rope.

Moments M_1' and M_2' are plotted below the reference line, since their tendency to rotate the reel is opposed to that of M_1 and M_2.

Denoting the moment of the total friction and windage by M_f the resultant moment M_0 of the ascending ore skip, rope and friction and the descending skip and rope is expressed by $M_0 = M_1+M_2-M_1'-M_2'+M_f$, which is the moment of the force, or the torque which must be applied to the reel to raise the ore.

The moment M_f of the friction is extremely difficult to obtain, and varies considerably with local conditions, but it is usually assumed to be approximately 15 per cent of the average value of $M_1+M_2-M_1'-M_2'$.

During the period of acceleration, a force additional to that required to raise the load and overcome friction, must be applied to the reel for accelerating the reels, ropes, etc. Assuming a uniform rate of acceleration, the moment M_3 of the force necessary for accelerating the ascending load, rope and one reel and clutch, may be determined from the equation

$$M_3 = \frac{\Sigma W S}{g t_a} p$$

where ΣW = the sum of the weights of the skip, ore, rope, one reel and clutch, and sheave reduced to a common radius of gyration p; S = the speed at the end of the radius of gyration in feet per second at the end of acceleration; $g = 32.2$, and t_a the time of acceleration in seconds.

Similarly, the moment M_3' of the force required for accelerating the descending skip, rope, etc., may be found from the equation

$$M_3' = \frac{\Sigma W' S}{g t_a} p$$

where $\Sigma W'$ = the sum of the weights of the descending skip, rope, reel, and sheave reduced to the radius of gyration p.

$$S = 2 \pi p R$$

Where R = the revolutions of the reel per second at full speed.

When the time allowed for making one complete trip is given, R may be found from the following equation

$$R = \frac{-r+\sqrt{r_1^2+\frac{2D}{\pi}}}{b} \times \frac{1}{T-.5\,(t_a+t_r)}$$

Where T = total time of lift in seconds (not including time for loading or dumping).

t_a = time for acceleration in seconds.

t_r = time for retardation in seconds.

At the end of the cycle all of the energy stored in the revolving parts of the hoist and its load is returned as the load is brought to rest. The moments M_4 and M_4' of the retarding forces may be found from the expressions for M_3 and M_3', respectively, substituting for $\Sigma\, W$ and $\Sigma\, W'$ the corresponding weights at the beginning of retardation.

Throughout the cycle there is a gradual increase in the speed of the ascending ore skip and unwound rope, and a similar decrease in the speed of the descending skip and unwound rope, but the accelerating and retarding forces are small and their moments may be neglected.

The resultant moments M_A and M_R during the periods of acceleration and retardation respectively are expressed by the equations

$$M_A = M_1+M_2+M_3+M_3'+M_F-M_1'-M_2'$$

$$M_R = M_1+M_2+M_F-M_1'-M_2'-M_4-M_O'.$$

M_A, $M_O\,M_R$ of Fig. 4 is the resultant moment diagram for balanced hoisting under the conditions assumed.

While hoists are generally operated in balance, it is frequently necessary to run them unbalanced for short periods while repairs are being made. The moment diagram $M_A\,M_O\,M_R$ for unbalanced hoisting is obtained from the equations

$$M_A = \frac{M_F}{2}+M_1+M_2+M_3$$

$$M_O = \frac{M_F}{2}+M_1+M_2$$

$$M_R = \frac{M_F}{2}+M_1+M_2-M_4$$

The speed of the ascending or descending skips in feet per minute, at any point, may be obtained from the equation

$$V = 120\,\pi\,r\,R$$

Cylindrical Drum Hoists. The cylindrical drum hoist is the type almost universally used for comparatively shallow shafts, and very frequently for the deeper ones. It consists of two cylindrical drums, upon which the rope is wound in one or more layers, the diameters of the drums varying from 5 or 6 feet to 25 feet.

The general equations for determining the several moments which make up the reel moment diagram, are made applicable to the cylindrical drum hoist by simply making b equal to zero.

For the cylindrical drum

$$R = \frac{O}{2\,\pi\,r} \times \frac{1}{T - .5\,(t_a + t_r)}$$

The moment diagrams for the cylindrical drum hoist are shown in Fig. 5. The notches in the diagram are due to the increase in diameter of the drum with each layer of rope.

By reference to the figure, it will be seen that M_0, the resultant moment of the ore skips and ropes, is very large at the first part of the cycle and decreases very rapidly toward the end of the cycle, this being due to the influences of M_1 and M_1', the moments of the rope. This difference in M_0 at the beginning and at the end of the cycle, increases with the depth of the shaft, the weight of ore per trip remaining constant; or for the same depth of shaft with reductions in the weight of ore hoisted, M_0 often becoming partially zero or negative toward the end of the cycle. The harmful effect of this extreme variation in M_0 is two-fold. First, the engine must be larger than otherwise necessary in order to start the hoist, and second, it operates at an inefficient cut-off at the end of the cycle. To reduce this variation in M_0 at the beginning and at the end of the cycle, the conical drum has been introduced.

Conical Drum Hoists. In the conical drum hoist, the ropes are wound in single layers on two large cones, the rope being wound from the small to the large end of the cone. The method of determining the moment diagrams is the same as for the reel hoist, making b equal to the increase in the radius of the cone for one turn of the rope. By reference to Fig. 6, which shows the moment diagrams for the conical drum hoist, it will be noted that

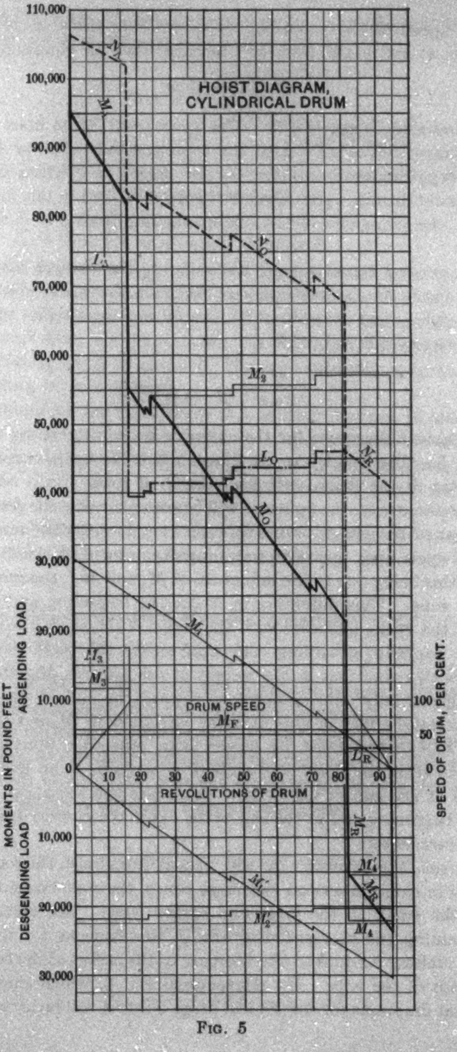
HOIST DIAGRAM,
CYLINDRICAL DRUM
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
10,000
20,000
30,000
MOMENTS IN POUND FEET
ASCENDING LOAD
DESCENDING LOAD
10
20
30
40
50
60
70
80
90
REVOLUTIONS OF DRUM
100
50
0
SPEED OF DRUM, PER CENT.
DRUM SPEED
N_A
M_A
L_A
N_O
M_2
L_O
N_R
M_O
M_1
M_3
M'_3
M_F
L_R
M_R
M'_4
M_R
M'_1
M'_2
M_4

Fig. 5

the unbalancing due to the rope in the shaft, has been entirely compensated for; in fact M_0 actually increases toward the end of the cycle. By varying the angle of the cone, M_0 may be made to increase or decrease toward the end of the cycle, or remain practically constant.

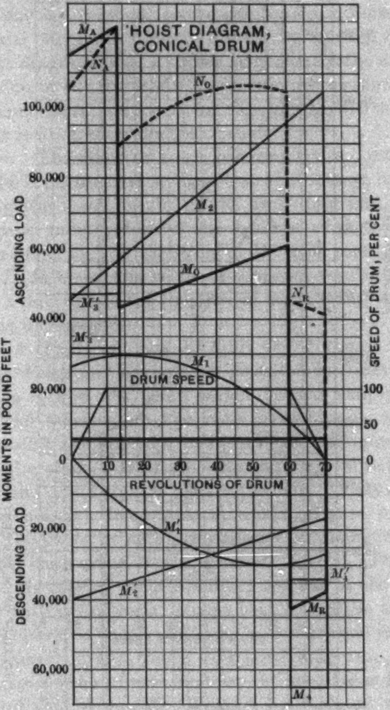

FIG. 6

Cylindro-conical Drum Hoist. The use of the conical drum as was the case with the reel, is limited to comparatively shallow shafts. For depths below which the use of the conical drum is impracticable, it is necessary to compromise, using a drum which as its name indicates, is a combination of cone and cylinder.

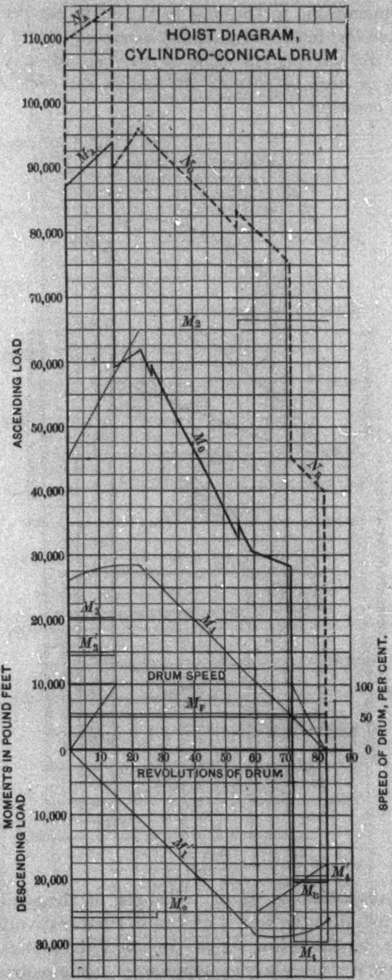
HOIST DIAGRAM,
CYLINDRO-CONICAL DRUM
N_3
M_3
N_0
M_2
M_0
N_4
M_1
M_3
M'_3
DRUM SPEED
M_F
M'_1
M'_0
M'_4
M_B
M_4
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
10,000
20,000
30,000
0
10
20
30
40
50
60
70
80
90
REVOLUTIONS OF DRUM
ASCENDING LOAD
MOMENTS IN POUND FEET
DESCENDING LOAD
SPEED OF DRUM, PER CENT.
100
50
0

FIG. 7

The rope is wound from the small end of the cone over the conical part of the drum in a single layer, then onto the cylindrical portion in one or more layers, depending upon the length of the rope. The load diagram is readily obtained by dividing the cycle into two parts, and treating the conical and cylindrical portions of the drum separately, determining the moments over the conical part as directed for the conical drum hoist, and over the cylindrical portion as directed for the cylindrical drum hoist. The moment diagram, Fig. 7 shows very clearly the effect of the conical portion of the drum, although the improvement in shape of the moment curve, over that for the cylindrical drum, is not so marked as it is for greater depths of shaft.

Tail Rope. The skips or cages are sometimes connected by a tail rope which passes over a sheave at the bottom of the shaft, thus making the total weight of the ascending and descending ropes the same, independent of the location of the cages in the shaft. The effect of the addition of the tail rope is shown in Fig. 5, L_A, L_0 L_R being the moment diagram resulting from the addition of a tail rope to the cylindrical drum hoist, which otherwise remains unchanged.

Koepe Disk Hoist. A type of hoist very common throughout Europe, but which has never been installed in America, is that known as the Koepe disk hoist, which consists simply of a large grooved wheel over which the rope passes once, the friction between the disk and the rope being sufficient to move the cages or skips in the shaft. Hoists of this type are always operated in balance and a tail rope is used with them. They are not well adapted for hoisting from several levels, because of the fixed position of the cages or skips, which can be changed only with difficulty to correspond with different levels. The moment diagram of this type of hoist is similar to that of the cylindrical drum hoist with a tail rope, except that b_0 will be a horizontal line, the notches due to the different layers of rope on the drum not being present in the Koepe disk hoist diagram.

Whiting Hoist. In order to increase the arc of contact between the rope and the wheel, Mr. Whiting substituted two narrow drums for the Koepe disk, the drums being placed one directly in front of the other, and the rope being passed four or five times over both drums. For the purpose of taking up the stretch in the rope and making small adjustments of the cages, one side of the rope is carried back over a moveable sheave mounted on a carriage resting on rails, the adjustments being made by chang-

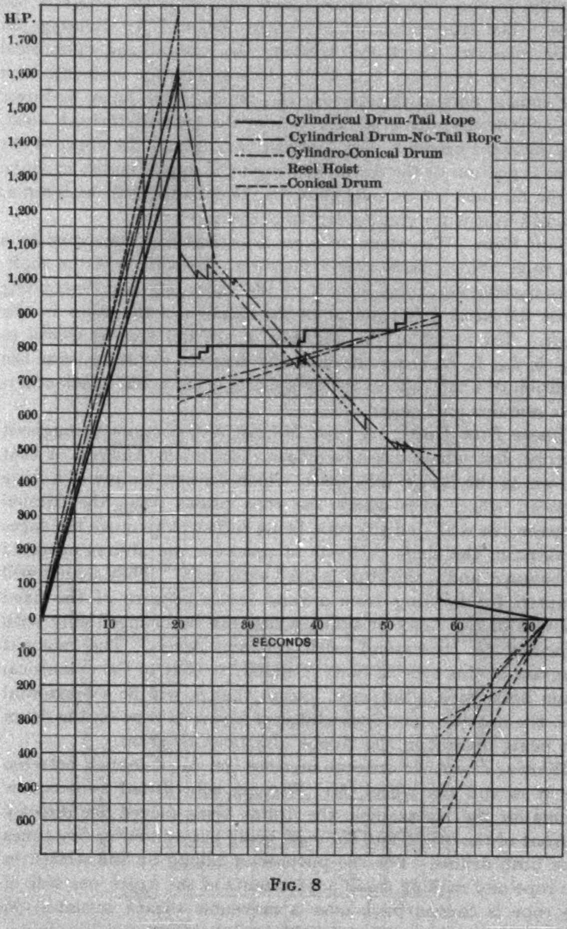
H.P.
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
10
20
30
40
50
60
70
SECONDS
Cylindrical Drum-Tail Rope
Cylindrical Drum-No-Tail Rope
Cylindro-Conical Drum
Reel Hoist
Conical Drum

FIG. 8

ing the position of the carriage. Whiting hoists are always operated in balance and seldom if ever without a tail rope. The moment diagram is exactly similar to that of the Koepe disk hoist.

The moment diagrams may be transformed into horse-power time diagrams by the use of the equation

$$\text{horse power} = \frac{2\pi M R}{550}$$

where M = the moment in pound feet and R = revolutions of the drum per second.

The horse-power diagrams corresponding to the moment diagrams of Figs. 4, 5. 6 and 7 are shown in Fig. 8, the curves for the balanced hoisting only being shown. Attention is called to the difference in the heights of the peaks during acceleration, the magnitude of these peaks having an important influence on the design of a motor for driving the hoist, its efficiency for the complete cycle, and the cost of power, if power is purchased.

SYSTEMS OF ELECTRIC HOISTING

The early application of electric power to mine hoisting was confined to small hoists, moving cars on inclines or hoisting light loads vertically from comparatively short depths. The complete success of these early installations led to the use of electric motors for winding from greater depths, until to-day ore is hoisted by electric power from some of the deepest mines in the world. The use of electric motors for driving the hoists, permits of the substitution of a large central electric generating station, which operates at a comparatively high load factor and which is placed where the conditions are more favorable for the economical development of power than they are at the mines, in place of isolated steam plants located at the shafts where condensing water is seldom available and where fuel is often expensive. The speed of the hoist motor when lowering unbalanced loads is automatically limited to approximately the hoisting speed. Safety devices in the nature of limit switches can readily be applied to prevent over-winding, and the acceleration of the hoist is made automatic; all of which tend to minimize the possibility of accident resulting from carelessness on the part of the operator. Not only is the speed limited when lowering unbalanced, but a large part of the energy, which with the steam-driven hoist is absorbed by the brakes, is returned to the electric supply system, thereby improving the economy of operation and reducing the wear on the mechanical brakes.

Many systems of electric hoisting have been proposed, each with the view of meeting some peculiar condition, or eliminating some real or apparent objection in the others, but virtually all the installations are confined to four systems, shown in Figs. 9, 12, 15 and 20. To assist in the comparison of the several systems, the authors have assumed a hoisting cycle, for both balanced and unbalanced operation, and have calculated the current and power taken by each system under the conditions assumed.

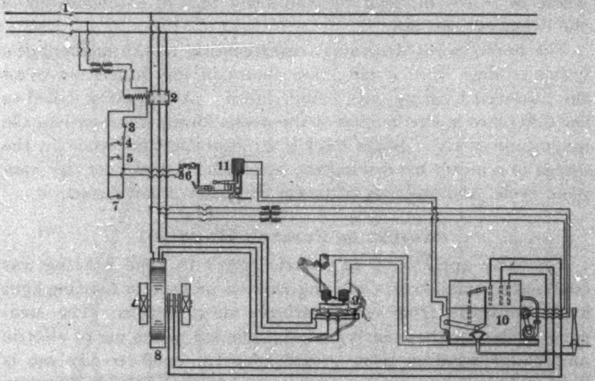

FIG. 9.—No. 1–2 Line switches. No. 3–4–5–6–7 safety switches for preventing overwinding and stopping the hoist, No. 8 hoist motor, No. 9 reversing switch, No. 10 liquid controller, No. 11, automatic brake.

The first and simplest system is shown in Fig. 9, and consists of a polyphase induction motor, direct connected or geared to the hoist drum. The speed of the motor is controlled by a variable resistance in its rotor circuit, which, because of the magnitude of the currents, involved, is usually some form of water rheostat. A common type of water rheostat consists of a tank, usually of boiler plate riveted together, and divided into two compartments; one the rheostat proper, and the other a cooling tank. The electrolyte is pumped from the cooling tank into the rhoestat proper, entering at the bottom of the rheostat and flowing out over the top of an adjustable weir, back into the cooling tank. The resistance in the rotor circuit is varied by changing the height of the electrolyte in the rheostat proper by means of the adjustable weir. The electrodes are usually thin iron plates hung on insulators, all phases being in the same compartment. At least one electrode per phase is of extra length, extending below the lowest level of the liquid, in order to prevent the rotor circuit from being opened. The most common form of electrolyte is a simple salt solution. The control of the rheostat is by means of a lever located on the operating stand.

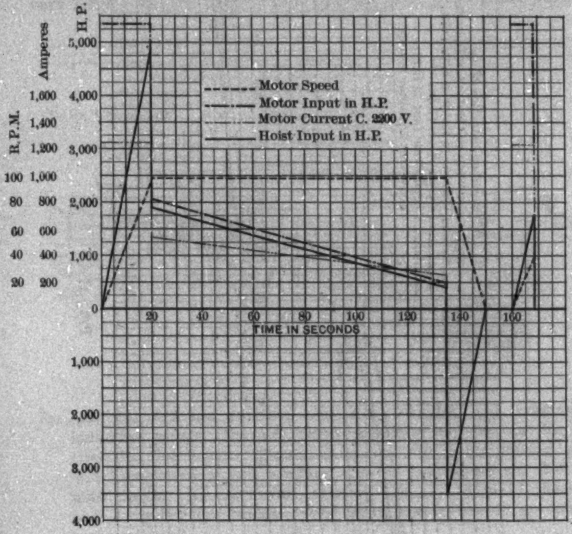

FIG. 10

Figs. 10 and 11 give the current and power curves for one complete balanced and unbalanced cycle, respectively. Frequently the cage is moved a few feet only, to obtain a proper setting of the cage or skip. The power taken for such short movements is shown by the right hand curves of Fig. 10. In these curves, as well as in those which apply to the other systems,

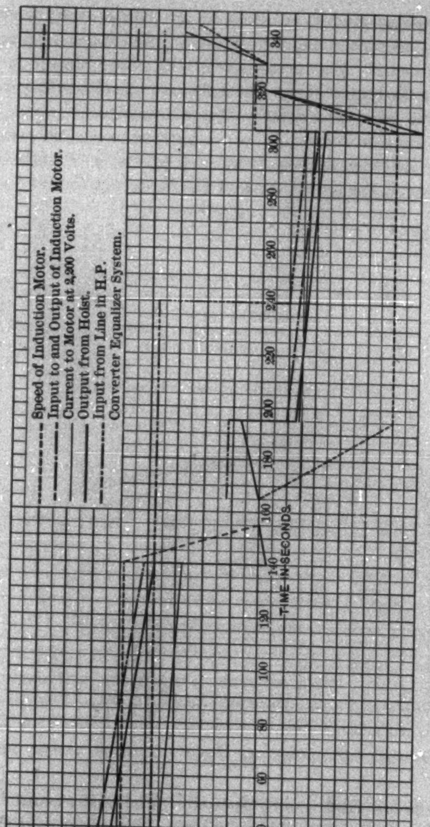
Speed of Induction Motor.
Input to and Output of Induction Motor.
Current to Motor at 2,300 Volts.
Output from Hoist.
Input from Line in H.P.
Converter Equalizer System.
H.P.
4,000
3,000
2,000
1,000
0
1,000
2,000
3,000
Amperes
1,000
800
600
400
200
R.P.M.
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
TIME IN SECONDS

FIG. 11

power delivered to the hoist is shown above the reference line and that returned by the hoist, below it.

By reference to the curves, it will be noted that the horse power and current taken by the motor are constant during the period of acceleration; that the efficiency for this period is very low, approximately 45 per cent; that no power is returned to the supply system during the period of retardation, and that the power consumption for small movements of the cage or skip is very large. On the other hand, the efficiency during the period when the hoist is running at full speed is high, approximately 90 per cent, and no power is consumed while the hoist is at rest.

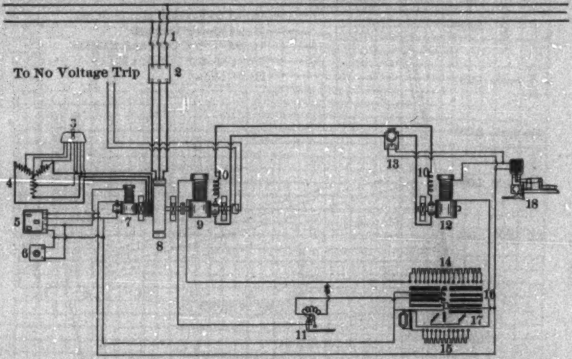

Fig. 12.—No. 1–2 line switches; No. 3–4 controller and resistance, induction motor; No. 5–6 Tirrill regulator and rheostat for exciter; No. 7–8–9 motor generator set; No. 10, commutating pole and compensating field winding; No. 11 safety device; No. 12 hoist motor; No. 13 circuit breaker; No. 14–15–16–17 rheostat and controller for generator and hoist motor; No. 18 automatic brake solenoid.

The efficiency over the complete cycle obviously decreases rapidly with a decrease in the time during which the hoist is driven at full speed. It follows from this that when hoisting is to be done from several levels, the efficiency at the maximum depth alone cannot be used as a basis for comparing the hoist driven by the induction motor with other systems. The efficiency of the cycle increases with an increased rate of acceleration, from which it follows that an induction motor for hoisting should be designed for a high maximum output to permit of a rapid acceleration.

The power returned to the system when lowering the empty skip unbalanced is shown by the right hand curves of Fig. 11. A comparison of the power taken by the motor in hoisting the loaded skip with that returned when it is lowered empty, shows that approximately 20 per cent of the power taken for hoisting is returned in lowering.

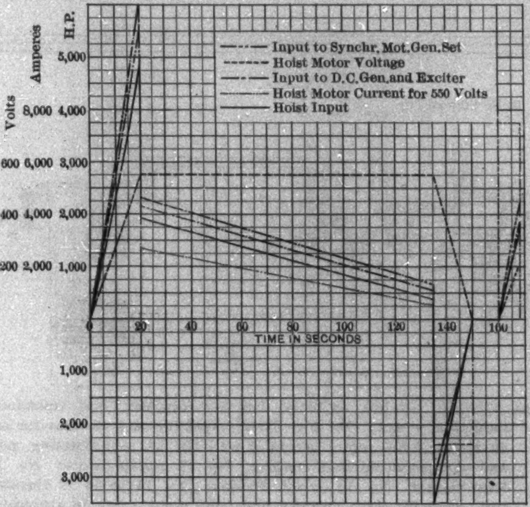

Fig. 13

The second system is that shown in Fig. 12. In this system the hoist is driven by a direct-current shunt-wound motor receiving power from the alternating-current supply system through a synchronous or induction-motor-generator set. The hoist motor is controlled by varying the voltage of the generator, which is separately excited, one generator being used for each motor.

The power and current curves for the balanced and unbalanced cycle, are shown in Figs. 13 and 14 respectively. These curves show that the power consumed during acceleration, is much

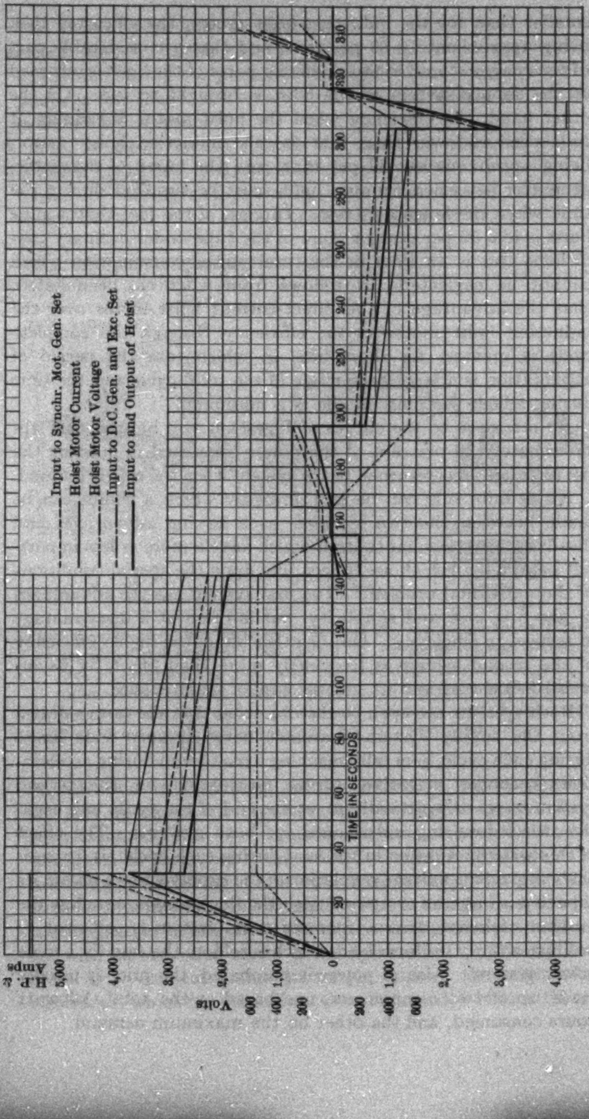
Input to Synchr. Mot. Gen. Set
Hoist Motor Current
Hoist Motor Voltage
Input to D.C. Gen. and Exc. Set
Input to and Output of Hoist
TIME IN SECONDS
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
H.P. & Amps
5,000
4,000
3,000
2,000
1,000
0
1,000
2,000
3,000
4,000
Volts
600
400
200
200
400
600

FIG. 14

smaller than for the induction hoist motor, the efficiency then being approximately 80 per cent, and that a considerable part of the energy stored in the revolving parts of the hoist is returned to the supply system as the hoist is brought to rest. On the other hand, the efficiency when the hoist motor is running at full speed, is lower than that for the induction hoist motor, being approximately 82 per cent, and the losses of the motor-generator set when running light, must be supplied during the time when the hoist is at rest. In view of the fact that a mine hoist is idle 50 per cent or more of the time under ordinary conditions, this is an item in the total power consumption which cannot be neglected. It follows from what has been stated, that the advantage of the direct-current hoist motor over the induction hoist motor in the efficiency through the complete cycle is greatest for short lifts, in which case the period of acceleration is a large percentage of the total cycle and the time during which the hoist is idle is a minimum.

By reference to the curves of Fig. 14 it will be seen that approximately 30 per cent of the power consumed in hoisting the ore unbalanced is returned to the system when the skip is lowered.

No definite rule can be laid down by which a choice can be made between the two systems, each having advantages and disadvantages peculiar to itself which have a more or less important bearing on the choice, depending upon the special conditions of the individual problem. The first system has the advantages of low first cost and simplicity, but is often at a disadvantage in respect to efficiency. On the other hand, the higher efficiency of the second system is frequently more than offset by its increased first cost and its greater cost of maintenance.

Both systems are open to the objection that the power drawn from the supply system fluctuates between very wide limits during each cycle, generally reaching a maximum during acceleration, becoming negative during retardation for the second system, zero, or practically so, at the end of the cycle, and negative when lowering unbalanced for both systems. The effect of this wide fluctuation in the load during each cycle, is to seriously impair the voltage regulation of the supply system unless its capacity is large as compared with the fluctuations, or unless the number of hoists driven from the same system is sufficient to produce a fairly uniform load, which is seldom the case for a mine power system. Also, if power is purchased, the price is usually made up of two components; one based on the total kilowatt hours consumed, and the other on the maximum demand.

It therefore becomes necessary in most cases to provide some means whereby power may be taken from the supply system and stored during the portion of the cycle when the demand for power is less than the average, and returned when the demand exceeds the average.

Fig. 15 shows such a system, the third, in which advantage is taken of the low first cost and efficiency of the flywheel as a means for storing and returning large quantities of power for short intervals. This system is similar to the second, except for the addition of a flywheel to the induction motor-generator set, and an automatic regulator for varying its speed. In its most common form, this regulator consists of a water rheostat connected in series with the induction motor armature. The resistance is varied by means of moveable electrodes suspended from an arm mounted on the shaft of an induction motor, which is connected in series, either directly or through series transformers, with the induction motor of the flywheel set. The regulator motor is so connected that its torque opposes the weight of the electrodes, which are partially counterbalanced to reduce the size

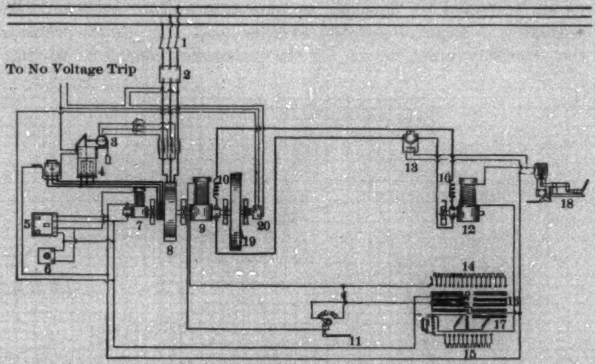

Fig. 15.—No. 1-2 line switches; No. 3-4 slip regulator; No. 5-6 Tirrill regulator and rheostat; No. 7-8-9-19 fly-wheel motor generator; No. 10 commutating pole and compensating field winding; No. 11 safety device; No. 12 hoist motor; No. 13 circuit breaker; No. 14-15-16-17 rheostat and controller of generator and hoist motor; No. 18 automatic brake solenoid; No. 20 speed limit device.

of the regulator motor to a minimum, and permit of an adjustment of the regulator for different values of line current. When the line current exceeds the value for which the regulator is adjusted, the torque of the motor overbalances the weight of the electrodes, lifting them and inserting resistance in the armature circuit of the induction motor. This causes it to slow down, and allows the flywheel to assist in driving the generator during the peak loads. The sensitiveness of this regulator varies with the line current, but within the range of ordinary operation the line current may readily be held within 5 per cent either side of the mean, provided the hoisting is done at a uniform rate and the regulator is adjusted for the average load. In actual practice the regulator must be set for the maximum condition, so that under ordinary conditions of hoisting, the current is limited rather than maintained constant.

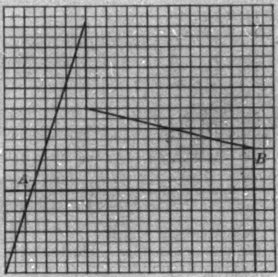

FIG. 16

The weight of the flywheel is determined from the hoist diagram by correcting it for the losses in the hoist motor and generator. Let Fig. 16 be such a diagram, and let *a*, *b* represent the average for the cycle. Then the energy represented by the portion of the diagram above the average line must be delivered by the flywheel during the peak load. The weight of the flywheel may be obtained from the equation

$$W = \frac{2gE}{Y_0^2 - Y_1^2}$$

where W = effective weight of wheel, Y_0 = the velocity of the wheel at a, Y_1 = the velocity of the wheel at b, and E = the energy in foot-pounds to be delivered by the wheel. It is the usual practice to make Y_0 approximately 300 ft. per second, in which cases the actual weight of the wheel is approximately equal to 1.33 W.

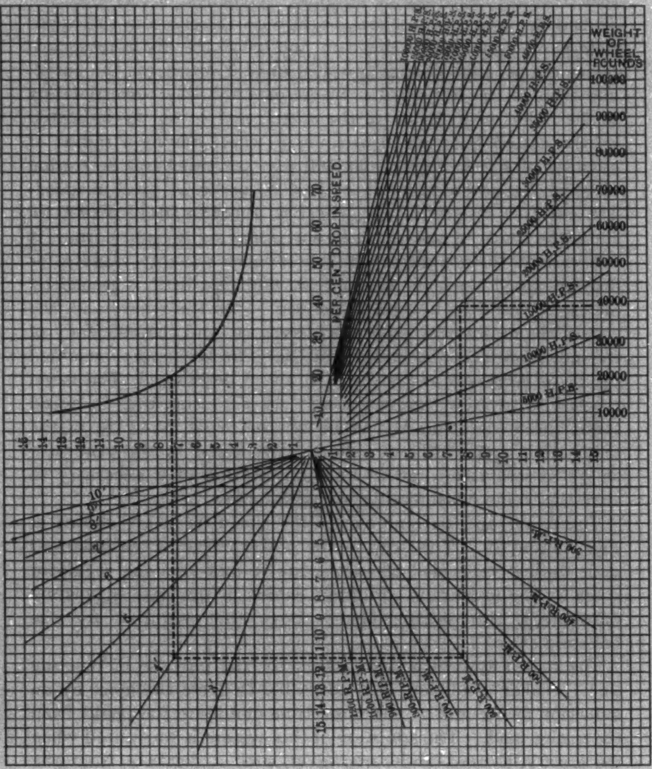

Fig. 17

A convenient method of obtaining the effective weight of a wheel is shown in Fig. 17. Having decided upon the radius of gyration in feet, and the speed in revolutions per minute, the weight of a wheel required to deliver any number of horse power seconds from 0 to 100,000 with any change of speed from 10 per cent to 70 per cent may be obtained by the use of this diagram. To find the weight of a wheel, begin with the curve in the upper right hand corner of the diagram, and follow the line corresponding to the per cent change in speed until it intersects the curve, and then to the left until it interesects the line corresponding to the radius of gyration of the wheel, and so on as indicated by the dotted line, which assumes a wheel having a radius of gyration of 4 feet, running at 600 rev. per min. and delivering 25,000 horse-power seconds with a 20 per cent drop in speed. The effective weight of the wheel is approximately 39,000 lb. From the shape of the curve in the upper right hand corner, it follows that the weight of the wheel increases very rapidly for drops in speed less than 15 per cent, and that little is gained by increasing the drop beyond 35 per cent. On the other hand, the cost of the motor and generator decreases, and the efficiency of the induction motor increases, and therefore the power consumed per cycle decreases as the drop in speed decreases. The usual practice is to allow approximately 15 per cent drop in speed for balanced operation, but as the flywheel must take care of the unbalanced cycle without reducing the speed of the generator so low as seriously to affect its commutation, it is necessary to vary this value considerably in special cases.

The power and current curves for this system are shown in Figs. 18 and 19. The drop in the power curve of the balanced cycle during the period of rest, is due to fact that the regulator is set for the maximum condition, which in this case is hoisting unbalanced, this setting being above that required for the balanced cycle.

The fourth system is used when, for the purpose of meeting some peculiar condition, it is advisable to drive the hoist by an induction motor and at the same time eliminate the peaks from the station load. The adoption of this system is warranted when the hoist is located underground at such a distance from the surface that it becomes necessary to transmit power to it by alternating current, and when the shaft is not large enough to allow the flywheel of the motor generator set, to be taken underground.

Fig. 20 shows this system, which it will be noted is the first system, to which has been added a converter equalizer, consisting of a rotary converter connected on the alternating-current side to the supply system, and on the direct-current side to a motor driving a large flywheel. The field of the direct-current motor is controlled by a regulator actuated by the line current. When the power taken by the hoist motor drops below the average, the field of the motor is automatically reduced, and the flywheel is speeded up, the power being taken from the supply system.

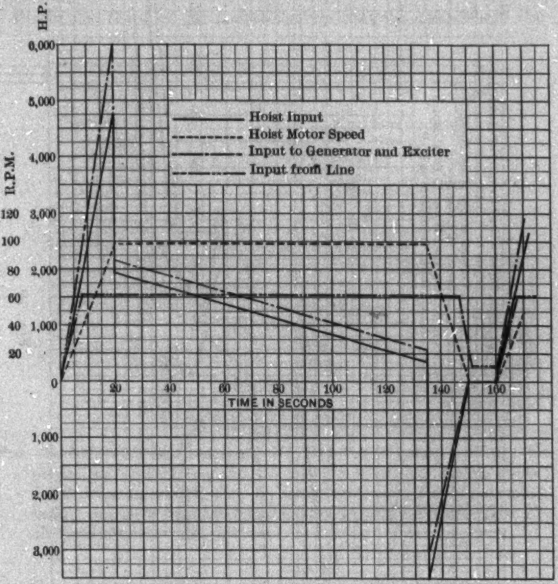

Fig. 18

When the hoist-motor load exceeds the average, the operation is reversed, the flywheel slowing down and returning power to the system.

Fig. 11 gives the current and power curves which are those of the first system to which has been added the input curve with converter equalizer. The efficiency of this system is generally slightly lower, and the weight of the flywheel is slightly greater

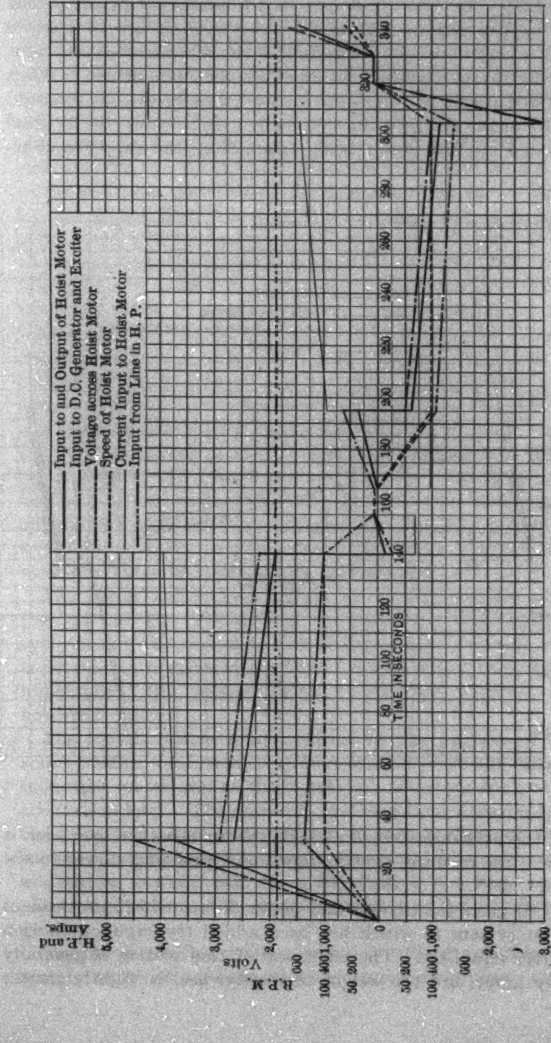
Input to and Output of Hoist Motor
Input to D.C. Generator and Exciter
Voltage across Hoist Motor
Speed of Hoist Motor
Current Input to Hoist Motor
Input from Line in H. P.
TIME IN SECONDS
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
H.P. and Amps.
5,000
4,000
3,000
2,000
1,000
0
1,000
2,000
3,000
Volts
600
400
200
200
400
600
R.P.M.
100
50
50
100

FIG. 19

than for the direct-current motor and the flywheel motor-generator set. It has the advantage, however, over the third system, in that the operation of the hoist motor is not dependent on the operation of a converter equalizer. Consequently in the event of the failure of the latter, hoisting may be continued, providing, of course, that the capacity of the power system is sufficient to take the load, which would be the case if the equalizer were used simply to reduce the power bill.

Either the third or the fourth system may be used where the supply system is direct current, by substituting a direct-current motor for the induction motor of the fly-wheel motor-generator set in the third system, and omitting the synchronous converter of the fly-wheel converter system in the fourth.

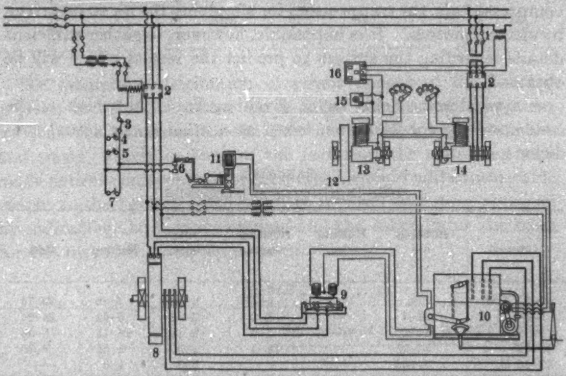

Fig. 20.—No. 1-2 line switches; No. 3-4-5-6-7 safety switches for preventing overwinding and stopping the hoist; No. 8 hoist motor; No. 9 reversing switch; No. 10 liquid controller; No 11 automatic brake; No. 12-13 fly-wheel dynamo; No. 14 rotary converter; No. 15-16 Tirril regulator and rheostat.

Among other systems of electric hoisting which might be mentioned, is the Creplet system, in which a booster driving a heavy fly-wheel is connected in series with the hoist motor and the supply system. The booster is wound for the same potential as the supply system, and the hoist motor for twice this potential. When the hoist is idle, the hoist motor armature is short-circuited, the booster is thus connected across the supply system and the speed of the flywheel is at its maximum. To accelerate the hoist, the short-circuit is opened, and the potential of the booster is gradually reduced to zero, reversed, and brought up to full potential in the opposite direction, the power stored in the flywheel during the idle period being returned.

It has been proposed, and at least two installations embodying the idea are now in process of construction, to substitute compressed air for steam. The present hoist engines would be used with slight modification of their valves to accommodate them to compressed air, the compressors for supplying the air to be driven by electric motors. It is impossible, however, to gather sufficient details regarding the system to predict the results which will be obtained.

A typical mine-hoist log is given in Table A, which is the condensed log for 24 hours, taken at a mine under actual conditions.

TABLE A

TIME IN MINUTES AND SECONDS

Interval	Hoisting ore	Hoisting men	Hoisting waste	Other hoisting	Shifting	Rest
7–8 A.M.	—	10–2	6–37	6–28	7–39	29–14
8–9	24–5	—	3–0	2–47	6–44	23–24
9–10	14–2	3–55	5–0	6–12	15–15	15–56
10–11	30–25	—	12–0	1–30	8–35	7–30
11–12 M.	57–55	—	—	1–5	1–0	—
12–1 P.M.	3–35	1–0	17–5	2–55	4–29	30–56
1–2	51–10	1–50	—	1–45	4–0	1–15
2–3	20–10	—	—	2–40	12–5	25–5
3–4	44–0	—	—	0–51	5–25	9–44
4–5	—	7–38	—	1–25	0–38	50–19
5–6	—	—	—	—	0–35	59–25
6–7	—	13–8	—	1–23	0–27	45–2
7–8	21–27	—	16–42	1–54	2–1	17–56
8–9	51–7	1–8	—	4–57	1–59	0–49
9–10	54–17	—	—	1–30	1–30	2–43
10–11	48–22	1–42	—	—	2–53	7–03
11–12 M.M.	—	—	8–39	4–16	0–40	46–25
12–1 A.M.	34–51	1–52	—	—	0–30	22–47
1–2	53–14	—	—	2–49	—	3–57
2–3	50–25	—	—	1–10	—	8–25
3–4	—	7–50	—	25–43	1–0	25–27
4–5	—	—	—	55–47	0–34	3–39
5–6	—	—	—	5–14	—	54–46
6–7	—	—	—	3–09	—	56–51

Table B gives a condensed summary of this log, and also that of another mine under actual operating conditions.

TABLE B

	Mine A			Mine B	
	Min.	Sec.	Per cent	Approx. min.	Approx. per cent
Hoisting ore and waste....	628	8	43.7	428	30
Other hoisting............	185	15	12.9	171	12
Shifting..................	77	59	5.4	120	8
Rest......................	548	38	38	721	50

The estimated distribution of power consumed for hoisting is given in Table C. Attention is called to the close agreement between the estimates for the power consumed in hoisting ore and waste, which, in view of the fact that the estimates were made entirely independent of each other, should add considerable weight to the figures. One estimate is based on figures obtained by indicating the hoisting engine, and the other forms the basis for the distribution of the costs of hoisting.

TABLE C

	Distribution of power in per cent of total	
	Mine A	Mine B
Hoisting ore and waste................	55	51
Other hoisting........................	28	23
Shifting..............................	17	26

The curves in Fig. 21 give the total tons hoisted, and the total kilowatt hours consumed (per day of 24 hours), the kilowatt hours consumed per ton (2000 lb.) foot, and the load factor for each of the four systems when hoisting 10,000 lb. per trip in balance from vertical depths, varying from 400 ft. to 2600 ft. by a reel hoist. Fig. 22 gives similar curves for hoisting 20,000 lb. of ore per trip in balance, from depths varying from 3000 ft. to 8000 ft., by a cylindrical drum hoist, the shaft making an angle of approximately 38 degrees with the horizontal, and the depths being measured on the incline.

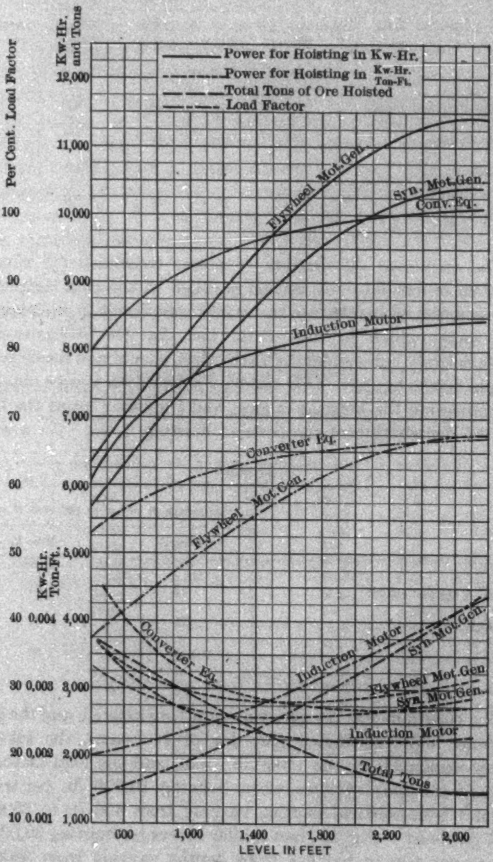
Power for Hoisting in Kw-Hr.
Power for Hoisting in Kw-Hr. / Ton-Ft.
Total Tons of Ore Hoisted
Load Factor
Per Cent. Load Factor
Kw-Hr. and Tons
Kw-Hr. / Ton-Ft.
12,000
11,000
100 10,000
90 9,000
80 8,000
70 7,000
60 6,000
50 5,000
40 0.004 4,000
30 0.003 3,000
20 0.002 2,000
10 0.001 1,000
600
1,000
1,400
1,800
2,200
2,600
LEVEL IN FEET
Flywheel Mot.Gen.
Syn. Mot.Gen.
Conv. Eq.
Induction Motor
Converter Eq.
Flywheel Mot.Gen.
Converter Eq.
Induction Motor
Syn. Mot.Gen.
Flywheel Mot.Gen
Syn. Mot.Gen.
Induction Motor
Total Tons

FIG. 21

Table D gives the power consumption for the various systems for hoisting 6000 lb. in balance from one level in a compound shaft, the hoist load diagram for which is given in Fig. 23. The shaft drops vertically 800 feet and then continues for 1320 feet on an incline of 38 degrees with the horizontal.

TABLE D

	Power for hoisting in kw-hr.	Power for hoisting in kw-hr, ton ft.		Total tons hoisted	Load factor
First system....	3900	0.00307*	0.00234†	786	25
Second "	3450	0.00272	0.00206	"	19.2
Third "	4019	0.00315	0.00240	"	62
Fourth "	4910	0.00386	0.00295	"	63.6

* Values are based on the total vertical lift 1613 feet.

† Values are based on the total distance lift 2120 feet.

The values given in these curves and table, include the power consumed in "other hoisting" and "shifting", on the assumption that the power consumed in hoisting ore is 53 per cent of the total power. Also in the values for the synchronous motor-generator set (second system) no credit is allowed for the power returned during retardation.

These curves and table show clearly the effect of the shape of the hoist diagram on the power consumed by the various systems. At the upper levels the period of acceleration is a large part of the total cycle, and we find the power consumed by the induction-motor hoist to be greater than that for the hoist driven by the direct-current motor, power for which is supplied by a synchronous or induction-motor-generator set. In the case of the cylindrical drum hoist, for which the peak during acceleration is much greater than for the reel hoist, the power consumed by the induction motor is greater for all levels. Also a similar relation exists in the power curve when a converter equalizer or a flywheel motor-generator set is used.

If a cylindrical drum is used instead of a reel, the curves of Fig. 21 for the direct-current hoist motors will remain practically the same, but those for the induction hoist motor will be raised, crossing those of the synchronous motor generator set toward the end of the curve; and if a cylindro-conical drum is substituted

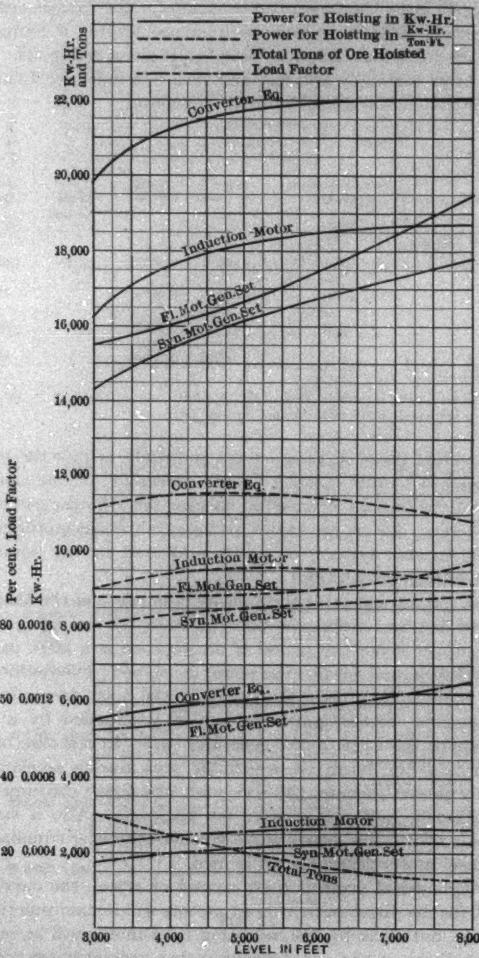
Power for Hoisting in Kw-Hr.
Power for Hoisting in $\frac{\text{Kw-Hr.}}{\text{Ton-Ft.}}$
Total Tons of Ore Hoisted
Load Factor
Kw-Hr. and Tons
Per cent. Load Factor
Kw-Hr.
22,000
20,000
18,000
16,000
14,000
12,000
10,000
80 0.0016 8,000
50 0.0012 6,000
40 0.0008 4,000
20 0.0004 2,000
Converter Eq.
Induction Motor
Fl. Mot. Gen. Set
Syn. Mot. Gen. Set
Converter Eq.
Induction Motor
Fl. Mot. Gen. Set
Syn. Mot. Gen. Set
Converter Eq.
Fl. Mot. Gen. Set
Induction Motor
Syn. Mot. Gen. Set
Total Tons
3,000
4,000
5,000
6,000
7,000
8,000
LEVEL IN FEET

Fig 22

for the cylindrical drum of the larger hoist, the induction-motor curves of Fig. 22 will approach those for the direct-current hoist motor.

The values for the different levels, shown by the curves, are based on the assumption that all the ore is taken from the corresponding level. Where ore is hoisted from several levels, the total power consumption per day may readily be obtained from the power consumption per ton foot, or by use of the curves of " Total Tons Hoisted " and " Power for Hoisting in Kw-hr."

While the curves given, cover specific cases only, the examples chosen are typical, and by interpolating between the power consumed per ton foot for the 8000 ft. and that for the 2500 ft. hoists, the power per ton foot may be obtained for hoisting from any depth. Due correction is to be made for the inclination of the 8000 ft. shaft by dividing the values given by 0.616 to obtain the equivalent values for a vertical shaft. From the total kilowatt hours consumed per day and the load factor, the cost of power for hoisting electrically can readily be obtained.

TABLE E

	Coal burned tons per day	Ore hoisted tons per day	Tons ore / tons coal
Hoisting from 2000 ft. level small hoist:			
Steam hoist..................................	47.0	1780	40
First system......................	13	"	137
Second "	15	"	119
Elec. hoist Third "	16	"	110
Fourth "	15	"	119
Hoisting from 6000 ft. level large hoist:			
Steam hoist..................................	65.5	1580	24
First system......................	23	"	69
Second "	24	"	66
Elec. hoist Third "	25	"	63
Fourth "	27	"	59

A comparison between steam and electric hoisting, is given in Table E in which the coal and rock ratio for each are given for the 2000 ft. and the 6000 ft. levels respectively. In determining these values, it is assumed that the steam hoisting engines are non-condensing; that the steam consumptions are 65 lb.

and 55 lb. per indicated horse-power hour respectively for the large and small hoists, and that power for the electric hoists is supplied from a modern steam-turbine station using units of 1000 kw. each, or larger for the smaller hoist and 2500 kw. or larger for the larger hoist.

In determining these ratios, 10 per cent has been added to the total kilowatt-hours per day as given in the curves, to cover the losses in transmission.

In addition to the saving in fuel which may be realized by the use of electric hoists, there is a very material reduction in the labor, the cost of which is chargeable against the hoist. This may amount to the wages of one or two men in the boiler house if power is developed by the mining company, or of the whole boiler-house force if power is purchased, and frequently the wages of one man in the hoist house.

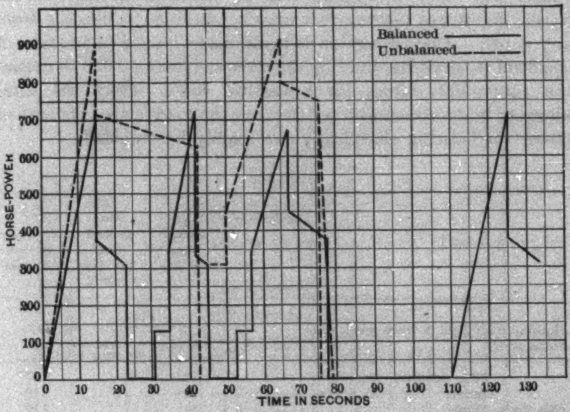

FIG. 23

So many factors which vary between wide limits for different localities enter into the comparative costs of hoisting electrically and by steam, that each individual case must be treated by itself, but the following comparison will serve as an indication of the general result of a more detailed investigation.

Take for example the reel hoist, the power curves for which are shown in Fig. 21, and assume that the average condition of hoisting is that represented by hoisting from the 2000 ft. level; that good steaming coal can be purchased for $3.50 per ton; that power can be purchased for the equivalent of 1.1c. per kw-hr., on a 50 per cent load factor, and, if steam driven, that the engine will be non-condensing.

In order to obtain a load factor of 50 per cent, it will be necessary to install either the third or fourth system of electric hoisting, and, to be conservative, let it be assumed that the third is chosen.

Total cost of power per year for electric hoist at 1.1c. per kw. hr	$35,300
Fixed charges on the excess cost of the electric over the steam hoist (approx. $25,000)	2,500
	$37,800
14100 tons coal at $3.50 per ton	$49,350
Boiler-house force (3 men at $3.25 per day)	2,925
One oiler	900
	$53,175
	37,800
Approximate annual saving with electric hoist	$15,375

As this saving of $15,375 is the result of an additional expenditure of $25,000 for the electric hoist, it is proper for a new installation to base the rate of interest equivalent to this saving on this additional first cost, from which it follows that the interest realized on this investment is 61.5 per cent. If, on the other hand, it is a question of replacing an existing steam hoist, the interest should be based on the total cost of the electric installation, in which case the very substantial rate of 30 per cent will be realized.

The hoist, above all other parts of the mine equipment, must be kept in commission at all times, and this fact must be borne in mind in installing an electric hoist. The transmission lines must be carried on substantial poles over a well-cleared right-of-way, duplicate lines being installed where possible and the lines being adequately protected against disturbances from lightning. If these precautions are properly taken, the electric can be made as thoroughly reliable as the steam-driven hoist.

Summing up, the advantages of the electric hoist are: first, greater economy, resulting from the centralization of the development of power in a large central electric station, favorably located for the economical development of power and from a reduction in the operating force, from the increased life of the rope and the greater life of the brakes; second, greater safety in operation; third, especially, adaptation for underground installations, and fourth, the fact that it permits of the utilization of water power which is frequently available in mining districts.

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LARGE ELECTRIC HOISTING PLANTS

BY WILFRED SYKES

The development of large electrically-driven hoisting plants has gone on simultaneously with that of balancing systems designed to equalize the input, thus relieving the generating stations of excessive peak loads. It will be readily understood that success from a commercial standpoint could hardly be hoped for with large plants requiring a maximum of 2000 or 3000 horse power unless the average load had some reasonable relation to the maximum, excepting, of course, those cases where the generating stations were of such capacity that the peak loads did not interfere with the operation or regulation of the plant generally. Such cases are, however, seldom met with, a notable instance being the mines at Johannesburg, which are to be supplied with power by the Victoria Falls Co. There it is intended to use three-phase motors up to 2000 h.p. maximum for hoisting, but owing to the large amount of power required for other purposes, the peak loads due to these motors will not materially affect the generating stations, which will have a capacity of about 100,000 kw. In the majority of cases where electric hoists are used the mines have either their own generating plants or purchase power under such conditions that the cost is materially affected by the load factor, and for economical working it is essential that the average load should be as high as possible. When a mine generates its own power it will usually be found that the proportion of the hoisting load to the rest of the requirements is very large, especially with deep mines, and the peak loads necessitate special provision being made to prevent them from interfering with the operation of the other part of the plant. The success of electric hoisting plants in

Europe when motors up to 3500 h.p. have been used, superseding steam hoists, has demonstrated that by carefully studying the subject there is no difficulty in securing very satisfactory results, not only from an operating, but also from a commercial standpoint. When considering large hoisting plants with the idea of driving them electrically it is essential that the load characteristics should be carefully studied, to determine not only the correct size of the machine, but also the system to be adopted. With steam-driven hoists this is not absolutely essential, for since the worst conditions are provided for, they cannot very well be overloaded; but as the output of electric motors is usually limited by the heating, rather than by the maximum safe load, the output at all points of the hoisting period must be known in order to design intelligently the electrical part of the equipment, including also any equalizing system which may be adopted. In this paper it is proposed to describe briefly some methods used by the author for the determination of load diagrams and also the characteristics of balancing systems and their economy.

Cylindrical drum hoists. This is the most common type of hoist and the load diagram is very simply obtained. Dealing first with a single-drum hoist, with one cage without any counter balance, the static moment at the beginning of the trip will be,

$$M = (W+Rl+C)\,r+F+A$$

when M = total moment or torque in ft. lb.
R = weight of rope per ft.
l = depth of shaft in ft.
C = weight of cage in lb. (including cars).
r = radius of drum in ft.
F = total friction expressed in ft. lb.
A = accelerating moment in ft. lb.
W = weight of load to be hoisted.

As the cage is hoisted, rope will be wound on the drum and the load will be correspondingly reduced. With electrically-driven hoists the rate of acceleration is usually constant so that the distance traveled during this period will be

$$S\,t \div 2$$

when S = full speed of hoist in ft. per second.
t = time of acceleration.

Therefore, at the end of the accelerating period the load will be,

$$M_1 = \left(W+C+Rl-\frac{S\,t\times R}{2}\right) r+F+A$$

The hoist having reached full speed the accelerating moment drops out giving,

$$M_2 = \left(W+C+Rl-\frac{S\,t\times R}{2}\right) r+F$$

During the full speed period the load will be uniformly reduced by the rope wound on the drum until at the end of this period there remains only the amount of rope corresponding to the distance traveled during retardation, or,

$$M_3 = \left(W+C+\frac{S\,t_2\,R}{2}\right) r+F$$

when t_2 = time of retardation.
To bring the load to rest the energy stored in the moving parts must be absorbed either in lifting the load or by the brakes. At the beginning of retardation the load is therefore,

$$M_4 = \left(W+C+\frac{S\,t_2\,R}{2}\right) r+F-V$$

when V = retarding moment.
At the end of the trip the load will be,

$$M_5 = (W+C)\,r+F-V$$

Considering the case of a double-drum hoist, the conditions are somewhat different as the cages balance one another. At starting we have

$$M = (W+R\,l)\,r+F+A$$

During acceleration the weight on the loaded side will be reduced by that of the rope wound on the drum, but from the second drum a corresponding length of rope will be unwound so that the effective load will be reduced by twice the weight of the rope wound on the drum, or,

$$M_1 = (W+R\,l - S\,t \times R)\,r+F+A$$

At the beginning of the full speed period the load is as above except that there is no accelerating moment. The load continues to decrease as the rope is wound on one drum and off the other, until at the end of the full speed run we have,

$$M_3 = (W-R\,l+S\,t_2\,R)\,r+F$$

At the beginning of retardation the load is

$$M_4 = (W-R\,l+S\,t_2\,R)\,r+F-V$$

and at the end of the trip,

$$M_5 = (W-R\,l)\,r+F-V$$

In order to work out the load diagram as above, it is of course necessary to have such data as weight of load, rope, cages, etc., but on the question of time and speed, acceleration and friction, a few remarks may not be out of place.

Time. As usually presented, the problem is to obtain a certain maximum output per hour, usually a good deal more than the average, so as to allow for delays. A certain time will be required for changing the cars and after deducting this from the time per trip, the actual hoisting time is obtained. This of course applies to balanced hoisting and, with a single cage, time must be allowed for lowering. If we suppose that our experience indicates that a certain period, $t+t_2$ will be reasonable for acceleration and retardation, the full hoisting speed will be,

$$S = \frac{l}{T - \frac{t+t_2}{2}}$$

when T = actual hoisting time; or supposing that the full speed is given, the time available for acceleration and retardation is

$$2\left(T - \frac{l}{S}\right)$$

Acceleration and retardation. The accelerating moment will depend upon the total mass of the moving parts and the velocity. It will generally be found convenient to reduce all the moments of inertia to the drum radius. The total will be made up of the load, cages, ropes, sheaves, drums, gearing and motor, the first three of which can be readily determined. The inertia of the sheaves will depend on the design, but if data are not available we may approximate by taking $\frac{W r_1^2}{g} = 25\, r_s^2$ for each sheave; when r_s = radius of sheave, and for each of the drums $100\, r^2 W'$ when W' = width of drum. These are of course only rough guides and the actual figures should be obtained if possible. If the weights are known it is safe to take the radius of gyration, or $r_1 = 0.8r$, in calculating the inertia. The gearing, if any, must be worked out from the weights and dimensions and the motor data can only be obtained by making a rough estimate of the size and picking out a suitable machine. The total amount of inertia I_1, reduced to the drum will be therefore,

Traveling parts $\frac{(W+2\,l\,R+2C)\, r^2}{32}$

Sheave $25\, r_s^2 \times \left(\frac{r_s}{r}\right)^2$

Drum $100\, r^2 W'$

Gearing $\frac{W r_1^2}{g} \times \left(\frac{O_1}{O}\right)^2 + \frac{W r_1^2}{g} \times \left(\frac{O_2}{O}\right)^2$ etc.

Motor $\frac{W r_1^2}{g} \times \left(\frac{M_s}{O}\right)^2$

When r_s = radius of sheave in ft.

O = speed of drums in rev. per min.

$O_1\, O_2$ = speed of the different parts of the gearing, O_1, being main gear $= O$, O_2 = countershaft speed and so on, each part of the gearing being worked out separately, M_s = motor speed.

The angular velocity of the drum is,

$$\omega = \frac{2\pi N}{60}$$

when N = rev. per min.

The accelerating moment is

$$A = \frac{I_1 \omega}{t}$$

and the retarding moment

$$V = \frac{I_1 \omega}{t_2}$$

Friction. The friction is very difficult to determine, as it varies with the condition of the shaft, cages, sheaves, hoist and speed. For moderate speeds the friction may be taken for a direct-coupled hoist as being equal to an extra load of from 5 per cent to 7½ per cent of the total suspended weight, including ropes, cages and load, and with a geared hoist, from 7½ per cent to 10 per cent, but this is only a rough guide and it is necessary to depend on experience more than anything else. Instead of calculating the static moment of the load at various points a very simple graphic method may be used. Referring to Fig. 1 draw $c\,d$ and $e\,f$ at right angles to $a\,b$, the distance between them being equal l/S, and on $c\,d$ lay off to a suitable scale the value corresponding to F, drawing $g\,h$ parallel to $a\,b$, and above this, fix the point $x = (W + Rl)\,r$, and also on $e\,f$ set off the value $y = (W - Rl)\,r$. On either side of $c\,d$ and $e\,f$ draw the verticals $j\,k$ and $l\,m$ and $n\,o$ and $p\,q$ at a distance representing half the period of acceleration and retardation respectively. Connect $x\,y$ and draw the horizontals $x\,w$ and $y\,v$. From the point where $x\,y$ intercepts $l\,m$ and $n\,o$, draw $x'w$ and $y_1\,v$. On $j\,w$ from w set off the value corresponding to the accelerating moment w_1 and draw parallel to $w\,x'$, $w_1\,x_2$ and on $v\,q$ from v the retarding moment v_1 drawing parallel to $y_1\,v$, $y_2\,v_1$. The complete torque diagram is the area $k\,w_1\,x_2\,x'\,y_1\,y_2\,v_1\,q$ and the total running line is shown by $k\,q$. To convert the values in ft.-lb. to horse power we must multiply by the angular velocity ω and divide by 550. For practical purposes we may consider that the current taken by the motor will be proportional to the torque and, as the heating depends upon the current, the torque diagram must be taken as the basis for calculating the capacity of the machine required. The usual method is to assume that the heating varies as the square of the current and that the heat is carried away from the motor at a constant rate. On this basis the size of the motor would be,

$$HP=\sqrt{\frac{\frac{HP_1^2+HP_2^2}{2}\times t+\frac{HP_3^2+HP_4^2}{2}\times t_1+\frac{HP_5^2+HP_6^2}{2}\times t_2}{T_1}}$$

when HP_1 HP_2 HP_3 HP_4 HP_5 and HP_6 correspond to the values at w_1 x_2 x' y_1 y_2 and v_1 respectively,

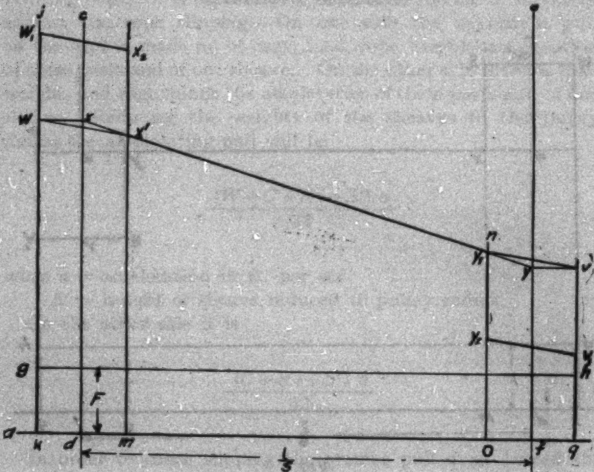

FIG. 1

t, t_1 and t_2 = time of acceleration, constant speed and retardation respectively,

T_1 = total time for each trip, including the period of rest.

This assumption is not altogether true for with induction motors there are extra losses in the rotor at starting, and with direct current machines the reverse is the case. The total losses do not increase exactly as the square of the current, nor is the heat carried away at the same rate all the time, but this gives a guide to the size of the motor required and if a proper allowance is made for these inaccuracies, the proper size of machine can be fixed very closely.

Whiting and Koepe hoists. These hoists are used to some extent, the latter very largely in Germany, and as a tail rope is generally used with the former, and always with the latter, they may be taken together. By using a tail rope of the same weight as the hoisting rope, the load to be hoisted becomes the only unbalanced part of the whole system and the diagram is very easily obtained. At the beginning of the trip the total load is

$$M = W\,r + F + A$$

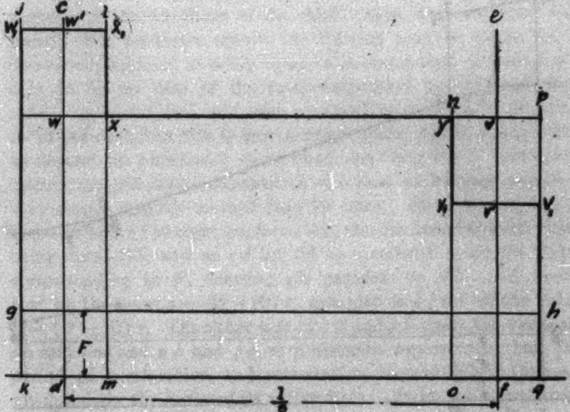

FIG. 2

At the end of the acceleration the only difference is that the accelerating moment disappears leaving

$$M_2 = W\,r + F$$

During retardation we have

$$M_3 = W\,r + F - V$$

The diagram may be readily obtained graphically as before. Referring to Fig. 2, set off $d\,f$ equal to l/S and draw $c\,d$ and $e\,f$.

Parallel to $a\,b$, plot $g\,h$ representing the friction, and above the $w\,v$ equal to $W\,r$. Draw $j\,k$, $l\,m$ and $n\,o$, $p\,q$ as before, the distance between them and $c\,d$ and $e\,f$ being equal to half the time for acceleration and retardation respectively. From w set off w' corresponding to the accelerating moment drawing $w_1\,x_1$ parallel to $w\,x$. From v set off v' corresponding to the retarding moment. drawing $y_1\,v_1$ parallel to $y\,v$. The area $k\,w_1\,x_1\,x\,y\,y_1\,v_1\,q$ represents the torque diagram for the motor which should be treated as before in order to determine the size of the motor. In connection with Koepe pulleys, and also to some extent with Whiting hoists, it is necessary to determine the factor of safety against the rope slipping. On one side the maximum pull on the rope is made up of cage, load, rope weight, acceleration of these parts and of one sheave. On the other side there is rope weight, and cage minus the acceleration of these parts and of one sheave. Reducing the weights of the sheaves to the pulley radius the accelerating pull will be

$$\frac{(W+C+Rl+S')\,a}{32}$$

when a = acceleration in ft. per sec.

S' = weight of sheave reduced to pulley radius.

On the other side it is

$$\frac{(C+Rl+S')\,a}{32}$$

In order to cause slipping the greater pull must exceed the smaller one multiplied by $e^{\alpha\mu}$ when

e = base of nat. log. 2.7182.

α = angle of contact of rope on sheave in radius.

μ = coefficient of friction between rope on pulley = 0.18.

Usually the angle of contact is about 190 degrees so that for the rope to slip we must have

$$\left\{ W+Rl+C+\frac{(W+Rl+C+S')\,a}{32} \right\} > 1.82 \left\{ Rl+C-\frac{(Rl+C+S')\,a}{32} \right\}$$

With Whiting hoists the angle of contact is 180 degrees and the multiplying factor is, 1.75 × number of wraps around driving sheaves.

Conical drum hoists. The determination of the load diagram for this type of hoist is somewhat more complicated than that for the hoists already dealt with. The object of conical drums is to compensate for the unbalanced load due to the rope, and to do this completely the following conditions must be met

$$r\,(W+Rl+C)-r_1\,C=r_1\,(W+C)-r\,(C+Rl)$$

when r = minimum radius.
r_1 = maximum radius.

This gives the proper dimensions for the beginning and end of the trip, but at intermediate points there are slight unbalanced loads if a plain conical drum is used. The variation from the ideal condition, however, is unimportant. From the smaller radius the greater can be obtained as follows:

$$r_1=r\left(1+\frac{2\,Rl}{2C+W}\right)$$

The length of the surface of the drum will be

$$L=\frac{l\times d}{\pi\,(r+r_1)}$$

when d = space required for each turn of the rope.

In order to obtain the same output as with a cylindrical drum the maximum speed will be approximately in the ratio of

$$\frac{r+r_1}{2}:r_1$$

which gives a value a little too high, as the rope is not at the maximum radius when retardation begins, but it is, however, near enough when making preliminary calculations in order to determine what average speed can be assumed. It will be found more convenient when dealing with this type of hoist to calculate the distance traveled in terms of revolutions of the drums instead of in feet. Supposing that a certain maximum speed S_{max} is fixed by considerations such as shaft construction, etc., the mean speed S_m will be

$$S_m = \frac{S_{max}\,\frac{r+r_1}{2}}{r_1}$$

which, expressed in revolutions per second, is

$$\text{Rev. per sec.} = \frac{\dfrac{S_{max}\,\frac{r+r_1}{2}}{r_1}}{2\pi\, 60\,\frac{r+r_1}{2}} = \frac{\dfrac{S_{max}}{r_1}}{2\pi\, 60}$$

The total number of revolutions to be made per trip is

$$\text{Rev. per trip} = \frac{l}{2\pi\,\frac{r+r_1}{2}}$$

The time available for acceleration and retardation is therefore:

$$t+t_2 = 2\left\{T - \frac{\dfrac{l}{2\pi\,\frac{r+r_1}{2}}}{\dfrac{\frac{S_{max}}{r_1}}{2\pi\, 60}}\right\} = 2\left\{T - \frac{\dfrac{2l}{r+r_1}}{\dfrac{S_{max}}{60\, r_1}}\right\}$$

$$= 2\left\{T - \frac{120\, l\, r}{S_{max}\,(r+r_1)}\right\}.$$

The speed in rev. per sec. being known, the revolutions can be readily found. The distance traveled during acceleration will be

$$l_1 = 2\pi\left(r + \frac{i\,z}{2}\right)z$$

i = increase in radius per turn = $r_1 - r \div$ rev. per trip
z = revolutions during acceleration.
z^1 = revolutions during retardation.

During retardation the distance traveled will be

$$l_2 = 2\pi \left(r_1 - \frac{i z^1}{2} \right) z^1$$

The inertia of conical drums may be taken as approximately, $200\,W' \frac{r^2 + r_1^2}{2}$ if the weight is not known.

Static moment. The variation of the static moment may be easily followed if the drum is considered as being extended so as to complete the cone with the apex at *a* Fig. 3. The area of the cone will be proportional to the square of the radius *O*, and as the weight of the rope on the drum will be proportional to the area covered, assuming an even spacing between the turns, it will be seen that it will also vary as the square of the distance from *a*. The length of the completing cone l' will be

$$l' = \frac{l \times r}{r_1 - r}.$$

The number of turns of rope on this part will be $\frac{l'}{d}$ when d = space taken by each turn of rope in ft.

and the length of rope $= \pi r \frac{l}{d}$

If the total weight of the rope on the drum and completing cone is considered as a separate load, none being wound on the drum, the static moment would vary with the distance from *a*, being $R\,L' \times$ radius. The amount of rope wound on the drum, however, varies with the square of the distance from *a* and the equivalent static moment as the cube; consequently the actual static moment for any point will be,

$$M_r = R\,L'\,r_2 - R\,L'\,r_1 \left(\frac{r_2}{r_1} \right)^3$$

when M_r = static moment of rope.
R = weight of rope in lb. per ft.
L' = total length of rope wound on drum and completing cone.
r_2 = any radius.
r_1 = maximum radius of drum.

From the above it is very easy to determine the static moment diagram by plotting a few points and drawing a curve through them; or graphic methods may be used.

Referring to Fig. 3, set off on $a\,b$ from a, the distance $a\,b'$ corresponding to the number of turns of rope on the drum and completing cone. Parallel to $a\,b$ draw $a_1\,b_1$, the distance between them being equal to $(L\,R+W+C)\,r_1$ and from b' drop the vertical $b'\,b_1'$. From the point a' corresponding to the smaller end of the drum, drop the vertical $a'\,a_1'$. A straight line from a to b_1'. would represent the static moment if none of the rope were wound on the drum, but, as pointed out, this value must be decreased by a certain amount, varying as the cube of the distance from a. On $b'\,b_1'$ lay off the value $L\,R\,r_1$ to Z leaving $z\,b_1'$ representing the actual static moment at the end of the trip and connect $a\,z$. If a cubic parabola is drawn between a and z, the distance between it and $a\,z$ will be the static moment diagram for the rope, and between the curve and $a\,b_1'$ the static moment diagram for the loaded side of the hoist. This may be done by a simple graphical method. Divide $a'\,b'$ into any number of parts and draw the verticals 2, 3, 4, etc. from $a\,b$ to $a_1\,b_1$. From the points of intersection with $a\,z$ draw the horizontals I, II, III, etc. to $b'\,b_1'$ and with $b'\,z$ as a diameter draw the semicircle. With b' as a centre describe the arcs $I\,I'$ $II\,II'$ $III\,III'$, etc., and from the intersections with the semicircle draw horizontals to $b'\,b_1'$ and from these points vectors to a. The intersection of I' and $a'\,a'_1$, II' and 2, III' and 3, etc., are points on the cubic parabola. This arrangement gives the diagram on the base $a\,b_1'$ but we can obtain it on $a_1\,b_1$ if, instead of drawing the vectors to a, they are drawn to a_1. The static moment for the unloaded side can be obtained in the same way. On $a'\,a_1'$ from a_1', lay off p corresponding to the static moment of the cage or $C\,r$ and draw $p\,z$. Parallel to $p\,z$ draw $I'\,I_1$, $II'\,II_1$, etc., and from the intersections with $a'\,a_1'$ the vectors to b_1, the distance of which from b_1' corresponds to the number of turns on the completing cone. The intersection of $I_1\,b_1$ with $b'\,b_1'$, $II_1\,b_1$ with 2, $III_1\,b_1$ with 3, etc., are points on the static moment diagram for the unloaded side. The distance between the two curves thus obtained is the resultant static moment for the hoist. In Fig. 3 a case has been taken where the static moment at the end of the trip is the same as at the beginning, the radii being obtained as already shown, and it will be noticed that the resultant moment is not quite a straight line, but the deviation is so small that it can be neglected. It will therefore be seen that if the condition for the complete compensation of the rope weight is met by properly proportioning the radii of the drum the static moment during the whole period may be taken as

$$M = (W+C)\,r - C\,r = W\,r$$

Inertia. It will be found convenient to reduce the inertia of the sheaves to the drum radius, assuming that it varies instead of the speed, which of course gives the same result. The equivalent

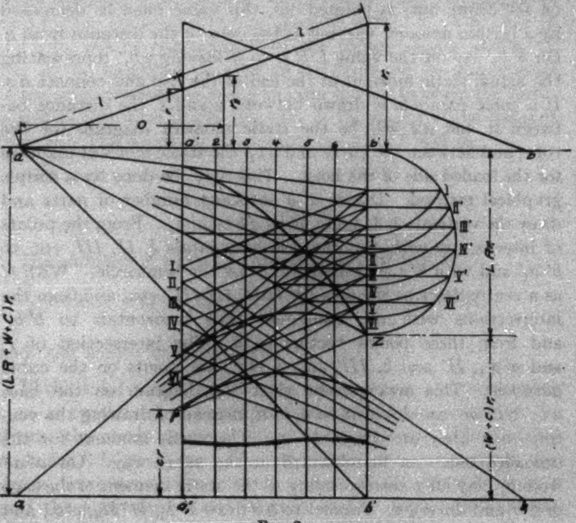
l
l
O
r
r_2
r_1
a
a'
2
3
4
5
6
b'
b
I'
II'
III'
IV'
V'
VI'
I.
II
III
IV
V
VI
I
II
III
IV
V
VI
Z
LR_1
$(LR+W+C)r_1$
$(W+C)r_1$
P
Cr
a
a_1'
b'
b_1

FIG. 3

inertia will therefore vary with the square of the drum radius, being a maximum at the larger radius when it is equal to

$$I_s \frac{r_s^2}{r_1^2}$$

in which I_s = inertia of sheave, and
r_s = radius of sheave.

If a simple parabolic curve is drawn from a point b' corresponding to the apex of the cone, Fig. 4 to the end of the drum on the line $b' b_1'$ the maximum value corresponding to $I_s \frac{r_s^2}{r_1^2}$, the part between the smaller and greater radii, $a_2 b_2$ corresponds to inertia of one sheave. By drawing a similar curve for the second sheave from b_1', $a_3 b_3$ will correspond to the inertia of the second drum and by adding the two the combined inertia curve $a_4 b_4$ may be obtained. It will be seen that this curve varies

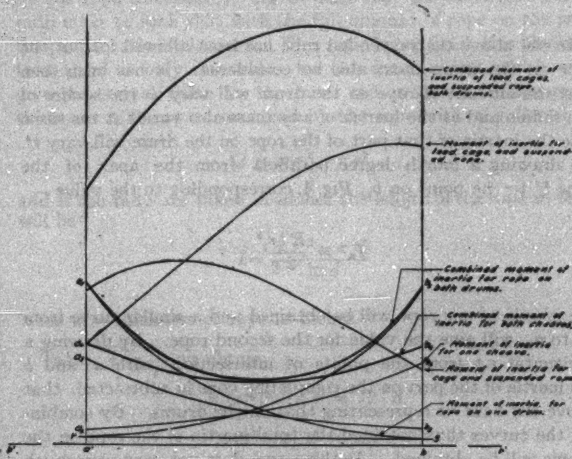

FIG. 4

very little from a straight line and for practical purposes the total inertia of the sheaves may be taken as constant at

$$I_{s1} = I_s \frac{r_s^2}{r^2} + I_s \frac{r_s^2}{r_1^2}$$

The inertia of the load and suspended rope may be obtained from the static moment diagram. As the moment of inertia is $\frac{W r^2}{g}$, if the static moment or $W r$ is multiplied by $\frac{r}{g}$

the various values are found, and by taking a few points and multiplying by the corresponding radius and dividing by 32, a curve is easily obtained.

The same must be done for the unloaded side, and the two curves which are thus obtained are combined. The form of these curves is shown in Fig. 4 and it will be found that for practical purposes no great inaccuracy will be introduced if the inertia is taken as the average of the two.

$$I_L = \frac{\left\{(W + C + Rl)\, r^2 + C\, r_1^2\right\} + \left\{(W + C)\, r_1^2 + (C + Rl)\, r^2\right\}}{2\,g}$$

In the above the suspended rope has been allowed for but the rope on the drum must also be considered. It has been seen that the amount of rope on the drum will vary as the square of the radius and as the inertia of any mass also varies at the same rate the inertia of that part of the rope on the drum will vary r^4. By drawing a fourth degree parabola from the apex of the cone b' to the point on b_5, Fig. 4, corresponding to the value

$$I_R = \frac{R\,l\,r_1^2}{2\,g}$$

the inertia of one rope will be obtained and a similar curve from b_1' to a_5, will give the value for the second rope. By drawing a horizontal $r\,s$ from the points of intersection with a' and b the inertia of the part on the completing cone is subtracted, that above the base $r\,s$ representing that on the drums. By combining the curves thus obtained the total inertia of the rope on the drums will be obtained. As this curve does not vary very much from a straight line and the total value is small, it is sufficient for practical purposes to consider the inertia of this part of the total as being constant at

$$I_{Rd} = \frac{R\,l\,\dfrac{r^2 + r_1^2}{2}}{g}$$

The inertia for all parts having been found, the load diagram may be determined in the same way as with cylindrical drum hoists.

Reel hoists. The reel hoist may be considered as a conical drum, the radius of which increases at each turn by an amount equal to the thickness of the rope. In order to compensate completely for the weight of the rope, the inner and outer radii must be determined in the same way as with a conical drum, the ratio being

$$r_1 = r\left(1+\frac{2\,R\,l}{2\,C+W}\right).$$

The increment by which the radius is increased being fixed by the rope thickness, it will be seen that the inner and outer radii must be such that with the full amount of rope on the reel the proper ratio is obtained. This ratio being fixed, it is obvious that there is only one value for the inner radius which will give the correct value for the outer radius with a certain rope thickness. The space occupied by the rope with a full reel is

$$Q = \pi\, r_1^2 - \pi\, r^2$$

and if the radii are taken in inches the length of the rope in feet will be

$$l = \frac{\pi\, r_1^2 - \pi\, r^2}{12\, d}$$

when d = thickness of rope in inches.

Taking $x = \frac{r_1}{r}$ we obtain,

$$\pi\,(x\,r)^2 - \pi\, r^2 = 12\, l\, d$$

$$\pi\,(x^2-1)\, r^2 = 12\, l\, d$$

$$r = \sqrt{\frac{12\, l\, d}{\pi\,(x^2-1)}}.$$

It may be that the value for r thus found will be too small for the size of the rope taken, the bending stresses being too high, and in this case it will be necessary to reduce the thickness and increase the width, but the permissible variation in this direction is comparatively small since only a few thicknesses are manufactured commercially. When the depth exceeds 1500 to 2000 ft. it will be found practically impossible to secure a complete compensation for the rope weight because the inner radius is so small that a suitable rope is not obtainable. Having fixed the radii, the load diagram may be determined in the same manner as that of a conical drum hoist.

Balancing systems. Practically all balancing systems utilize a flywheel, the speed of which is varied so that it gives up or absorbs energy according to the demands of the system. A storage battery may also be used for the same purpose and under certain circumstances it may be more economical than a flywheel, as the losses with the latter are constant and independent of the load, while the storage battery losses only occur when the battery is being used.

The main requirements of a balancing system are that it should be capable of preventing the peaks from coming on generating stations, it should be automatic in action, and the losses connected with it should be as low as possible.

The first practical system to be introduced was that proposed by Mr. Carl Ilgner, which, in various modified forms, has been very widely adopted for all classes of heavy work where greatly fluctuating loads have been taken care of. The Ilgner system as arranged for use with an alternating current source of supply consists of an alternating current induction motor with a wound rotor, coupled to a direct current generator, which, in turn, feeds a direct-current shunt-wound hoist motor. Coupled to the motor generator is a suitable flywheel designed to take care of the peak loads. The fields of the hoist motor and of the direct current generator are excited separately by a small exciter coupled to the motor generator set, means being provided for automatically maintaining its voltage constant when the speed of the set varies. The speed of the motor generator set is controlled by means of an automatic slip regulator operated by the line current. The scheme of operation is as follows:

At the beginning of a hoist cycle the flywheel will be running at full speed, all resistance being cut out of the motor rotor. In order to start the hoist, the generator will be gradually excited in the proper way to obtain the desired direction of rotation. As the speed of the hoist motor with constant field excitation will be practically proportional to the voltage of the generator, when the latter is increased the speed of the hoist will also increase until with full voltage the maximum speed is obtained. The only rheostatic losses at starting are those in the regulator controlling the generator field, which are negligible.

When the load on the induction motor exceeds the mean value for which the slip regulator is set, resistance is automatically introduced into the rotor so as to cause a reduction of speed, thus enabling the flywheel to give out a portion of energy stored in it and thereby assisting the motor to drive the generator. The speed will be automatically reduced so as to maintain constant input to the three-phase motor until the fly-wheel has given out all the energy required in excess of the mean value. When the load falls below this mean value the regulator will cut out the resistance in the rotor causing the set to increase in speed, thus storing energy in the flywheel and keeping the demand on the line constant.

The use of resistance in the rotor of the three-phase motor introduces a certain loss which will average half the slip between full and minimum speeds, but, as a rule, this loss is comparatively small compared with the output of the plant.

The question as to the most economical value to adopt is a very complicated one, depending as it does upon the first cost of the flywheel, the running losses, the time the plant is in service, etc. It will be seen that should the plant run for considerable periods without load it might be advisable to allow a fairly large slip and to use a light fly wheel so that the constant loss would be small. On the other hand, if the plant runs continuously, the intervals between trips being short, the slip regulator losses will bear a totally different relation to the input, and under such circumstances a relatively small slip and a heavy flywheel might be the most economical arrangement. It has been found in practice that a slip of 12 per cent to 15 per cent is about the most economical value, although in some plants a slip up to 20 per cent is provided for. Since the energy stored in the flywheel is proportional to the square of the velocity, it will be seen that by increasing the slip a proportional increase is not obtained in the output. Thus with a 15 per cent slip the energy available will be 28 per cent of the total stored in the flywheel. With 20 per cent slip the amount available is only increased to 36 per cent.

The Ilgner, or motor generator arrangement, is the most important of all equalizing systems, probably 90 per cent of the plants installed being designed on this principle. It will be noted that the whole of the power used by the hoist is transformed and also that there are no rheostatic losses at starting.

Fig. 5 shows the general connections of a hoisting plant on the Ilgner system with alternating current supply and from the description given the functions of the various parts will be easily followed.

Another system of importance, suitable for alternating current, which has a quite large field of application, is that known as the converter system, the principle of which is altogether different from that of the Ilgner system.

Fig. 6 shows the connections of this system as applied to three-phase hoisting plants. The hoist motor in this case is of the three-phase induction type with a wound rotor, being started by means of a rheostat. In order to equalize the demand on the line, the equalizing system is connected in parallel with the generator station. It consists of a rotary converter and a direct current machine to which is coupled a suitable flywheel. The operation of the arrangement is as follows:

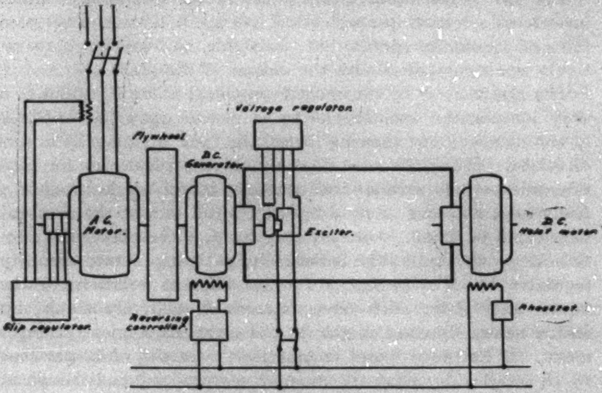

FIG. 5

The rotary converter acts only as a connecting link between the alternating current system and the equalizing set, which consists of a shunt-wound direct-current machine and the fly wheel. The field of this machine is controlled by a regulator, operated by the main line current. At the beginning of a trip the flywheel is running at full speed, and when the load exceeds the mean value, the regulator automatically strengthens the field of the equalizing machine so that it acts as a generator driven by the flywheel. The amount of energy given to the line will depend on the requirements in excess of the mean, as the regulator will continue to cut out resistance so long as there is any tendency for the line current to increase above the mean.

When the demand drops below the average the regulator will weaken the field, causing the machine to run as a motor, which taking energy from the line, speeds up the flywheel, the rate at which resistance is introduced to the field depending on the difference between the demand on the line and the mean load. In this way energy is stored in the flywheel and the line load is kept constant. The rotary converter changes either direct current to alternating current or vice versa, depending on whether the flywheel set is giving up or absorbing energy. It will be seen that the speed variation is obtained by field regulation, so that the loss is negligible, whereas with the Ilgner system it is from 7½ per cent to 10 per cent of the input to the driving motor. This is a very important feature in equalizing systems with direct current machines, as a much greater slip can be economically obtained, it being the usual practice to allow from 20 per cent to 25 per cent, and consequently the fly wheels can be comparatively light. The machines of the equalizing set need only be large enough to deal with the loads which exceed the mean value, and under ordinary circumstances the capacity will not be more than about half that of a motor generator set for the same duty. The equalizing equipment is quite independent of the hoisting motor, so that it may be out of service and the only difference will be that the peak loads will come on the line,

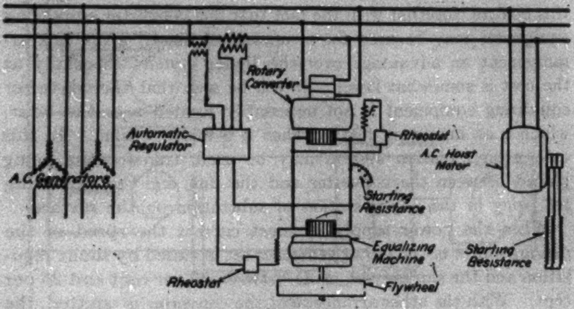

Fig. 6

but with the Ilgner system the hoist is dependent upon the motor generator.

The main difference between the two systems is that the Ilgner method provides for starting the hoist motor by voltage control without any rheostatic losses, while the converter arrangement makes no provision for doing so. When considering the economy of both systems this difference must be considered, as starting losses are often a large proportion of the total input. The question of starting is one of the most important ones with large hoists, and on this account the Ilgner system is preferred for heavy work. Motor generator sets without flywheels have been installed in a number of instances for the sole purpose of obtaining a simple and efficient method of starting. With small hoists the starting devices are not difficult to design and this feature, together with the fact that one converter equalizing equipment may be used for a number of hoists, gives this arrangement an advantage over the Ilgner system, especially as the cost is somewhat lower. It will be seen that the converter equalizing equipment is not necessarily located near the hoist, which is an important feature when it is inside a mine. In this case a high tension system may be used, transformers being placed between the converter and the line, and the equalizing set being in the power station or substation on the surface.

When the power supply is direct current the speed of the driving motor of the motor generator set is varied by shunt regulation and the slip may be made between 20 per cent and 25 per cent. With the other arrangement the converter is omitted, the equalizing machine being connected directly across the line. This latter arrangement is very simple, and so long as the starting of the motors can be done rheostatically, it appears to be the most reasonable system to use. A number of variations of the above arrangements have been employed but the principles are the same. There is another arrangement which under certain circumstances has some value. Its main feature is a reversible booster set, the voltage of which is the same as the line voltage. The general arrangement is shown in Fig. 7, from which it will be seen that the starting of the hoist motor is arranged for by regulating the booster field. When the hoist is at rest the booster has full field, both the booster and the motor running as motors off the line, a small current always passing through the hoist motor. When the hoist is started the booster field is weakened, the back e.m.f. being reduced, and a current flows through the hoist motor sufficient to start it. The difference between the input of the hoist and the load on the line corresponding to the current taken, is used by the booster, running as a motor, to drive the motor as a generator, thus returning power to the line. The field of the booster is gradually reduced until it is zero, when the line voltage will be applied directly to the hoist motor. The field is now reversed and the booster voltage is added to that of the line until with full excitation the pressure across the hoist motor is twice that of the supply system. This arrangement is manifestly only suitable where the line voltage is low and is not more than half the maximum pressure for which the motor can be conveniently built. The size of the booster set will be half the total input to the hoist motor. By adding a flywheel to the set and by providing for automatic regulation of the motor field the line load may be equalized. In the case of large plants, two hoist motors may be used connected in series and a supply voltage of 500 to 600 volts may be adopted, giving 1000 to 1200 volts at the motors.

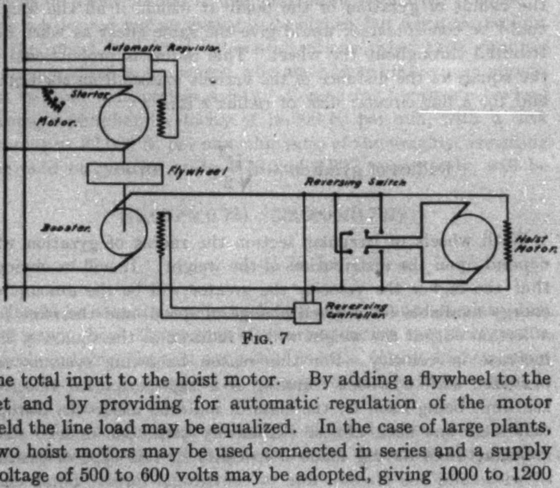

FIG. 7

Characteristics of balancing systems. The load diagram for the hoist motor having been determined as already described, it is used as a basis for the calculation of the dimensions of the fly wheel and the output of the various machines required according to the systems adopted. Dealing first with general principles, it will be noted that the energy in any moving body is

$$E = \frac{W V^2}{2 g}$$

when E = energy in ft. lb. per sec., from which it will be obvious that for any variation of speed the energy given up or absorbed will be proportional to the square of the minimum and maximum velocities, or,

$$E = \frac{W\,(V^2 - V_1^2)}{2g}$$

when V = maximum velocity in ft. per sec.
V_1 = minimum velocity in ft. per sec.

In the case of a revolving wheel the velocity taken is that at the radius of gyration or the point at which, if all the weight could be concentrated, would give the same effect as when distributed throughout the wheel. This radius is proportional to the square of the distance of the various masses from the center and for a flat circular disk of radius r it is

$$\text{Radius of gyration} = \sqrt{\frac{r^2}{2}} = 0.707\,r$$

With wheels of irregular section the radius of gyration will depend upon the distribution of the weight. It will be obvious that the higher the velocity the greater will be the amount of energy available for a given change of speed, and therefore for a certain output the weight will be reduced as the square of the increase in velocity. For this reason balancing systems are provided with flywheels running at a high peripheral velocity, the limit being fixed by the class of material used. In Europe cast steel has been almost exclusively used, one or two steel manufacturers having made a specialty of this type of casting to withstand the stresses due to centrifugal force. Small cast steel wheels have been built for peripheral speeds up to about 23,000 ft. per min., but for large wheels, on account of the difficulty of obtaining sound castings, the limit is in the neighborhood of 17,000 to 18,000 ft. per min. By carefully designing such wheels the radius of gyration may be made somewhat greater than that of a plain disk and the average of a number of cases worked out by the author gave the value of $0.78\,r$.

It will be understood that the permissible stresses in a cast steel wheel must be lower than those of a mild steel plate on account of the uncertainty as to the quality of the casting and the difference in the strength of the two, since with the latter, if the thickness is not too great, a perfectly homogeneous material can be obtained. For this reason the author has used flywheels built up of ordinary commercial steel plate. As the strength of the material and the stresses may be accurately determined it is quite permissible to run such wheels up to 24,000 or 25,000 ft. per min., if desired, without the stresses exceeding more than about half the elastic limit. Although the radius of gyration of such a wheel is somewhat less than that of a well-designed cast steel wheel, the increase in velocity permissible more than compensates for this difference. In plants already installed, speeds of about 22,000 ft. per min. have been used because it was not desired nor necessary to go higher, but when the weight of the wheel is limited by considerations other than running economy, there is no reason why the higher limits given should not be used with perfect safety. Comparing a cast steel wheel having a peripheral velocity of 18,000 ft. per min. with a disk running at 22,000 ft. per min. this ratio of the weights, assuming the radii of gyration to be 0.78 and 0.707 respectively, will be

$$(18{,}000^2 \times 0.78) : (22{,}000 \times 0.707)$$

or

$$1 : 1.35$$

It will be seen that under ordinary circumstances a plain disk will weigh about 74 per cent of a corresponding cast steel profile wheel, and since the cost per pound is little, if any, higher, when the difference in weights is considered, the built-up wheel is actually cheaper.

In order to determine the weight of the flywheel required to equalize any given load, it is necessary to determine the amount of energy which it must give out each hoisting cycle. In the case of the Ilgner system, the load on the driving motor will be made up of the output of the hoist motor plus the losses in both the motor and generator, so that in order to maintain the line load constant the flywheel must take care of all the excess of input to the generator above the mean value. The input diagram for the generator is easily obtained by taking the main points of the hoist motor diagram and adding the various losses corresponding to these points. For the sake of convenience the losses in the hoist motor and the generator may be assumed to consist of two parts; one, due to iron losses, friction and windage being constant; and the other, due to the copper and brush drop, varying with the square of the load. The excitation is provided for separately and need not be considered when determining the generator input.

It should be noted that the power diagram and not the torque diagram must be taken as a basis, as the actual input to the hoist is the product of the torque and speed, being zero at the beginning of the trip and a maximum when full speed is obtained When a motor is rheostatically controlled the difference between the power and torque diagrams is absorbed by the resistances, but with voltage control these losses are obviated. In Fig. 8 which is a load diagram for a Koepe hoist, the shaded portion represents the loss due to rheostatic control, and the area enclosed by *a b c d e* and *f* the power diagram.

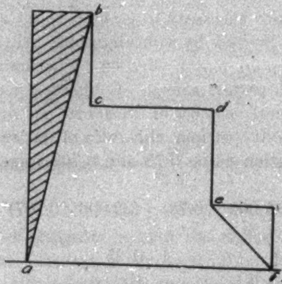

FIG. 8

The most convenient method for calculating the losses is to plot a curve made up as above, which can easily be done when the characteristics of the machines which it is intended to use are known. The load diagram will be a sufficient guide as to the size of the hoist motor and the generator, the latter being taken as about 10 per cent larger than the former. When, as is frequently the case, the hoist returns energy to the system during retardation, it should be noted that the losses in the two machines must be subtracted from the values obtained from the load diagram. The input diagram for the generator having been determined, the mean output of the three-phase motor is readily obtained. From the various loads and the times that they are applied, the total input per trip in horse power seconds is found, and if this value is divided by the total time required for one trip, including the period of rest when loading and unloading the cages, the average input is found. Taking this as the motor output for the time being, the loads in excess of this value will have to be taken by the flywheel. If energy is returned to the system by the hoist this value must be subtracted from the total before determining the mean input. Referring to Fig. 9 the line *a b* represents the mean input to the generator and the shaded portion the fly wheel output. It will be obvious that as the mean load is carried by the motor, the same amount of energy will be imparted to the flywheel during the periods when the demand is below the average as is given up during the time when it exceeds this figure. Therefore at the end of the cycle the flywheel will be running at the full speed again. Taking the flywheel output in h.p. sec., as found from the input diagram the weight required will be

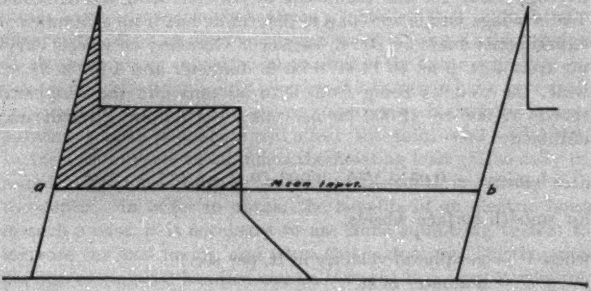

FIG. 9

$$W \frac{E' \times 550 \times 2\,g}{V^2 - V_1^2}$$

when W = flywheel weight in lb.
E' = flywheel output in h.p. sec.
g = 32.2.

V = maximum velocity at radius of gyration in ft. per sec.

V_1 = minimum velocity at radius of gyration in ft. per sec.

The flywheel output is multiplied by 550 to reduce it to ft. lb. sec. The actual output of the three-phase motor will be the mean load as found from the diagram plus the losses due to windage and friction of the flywheel, the average slip regulator loss which is equal to half the maximum slip, and the power required to drive the exciter. The friction of the flywheel bearings is readily found when the size of the bearings is known, an average value for the coefficient of friction being about 0.004. The windage loss is not easy to determine but from a number of experiments made by Dr. E. Becker in Germany on wheels varying from 6 ft. 6 in. to 14 ft. 6 in. in diameter and 4 in. to 31 in. wide, the weights being from 3 to 50 tons and the peripheral speeds 18,000 to 21,000 ft. per min., the following result was obtained,

$$\text{h.p.loss} = 0.0513\, V^{2.5} \times 0.093\, D^2\, (1 + 0.465\, B^2)\, 10^{-5}$$

for smooth surface wheels.

when V = peripheral velocity in ft. per sec.

D = diameter in ft.

B = width in ft.

The wheels tested gave results corresponding so closely to the above that it would appear to be fairly reliable.

In the case of the converter system only the part of the load diagram above the mean value is to be considered, the remainder having no influence on the balancing plant. Taking the loads in excess of the mean value found from the load diagram plus the hoist motor losses the actual output of the flywheel will be this amount plus the losses in the converter and equalizing machine, which must also include the excitation. The flywheel weight is then determined in the same way as with the motor generator system. It should be noted that the average input to the motor must include the rheostatic losses at starting or, in other words, the torque diagram must be taken and not the actual power diagram, as with the Ilgner system. The real demand on the line will equal the average found as above, plus the losses in the equalizing system which are caused by the double conversion, and the flywheel windage and friction. In the case of a motor generator system with a direct current driving motor, there is no loss due to the slip regulator, because all the regulation is in the motor field and the loss is negligible. With the converter system applied to a direct current plant there are no converter losses. These two systems contain the principles of all other equalizing arrangements and the same methods here indicated can be used for determining the characteristics of the different parts of any proposed system.

Economy of electric hoisting. When considering hoisting installations it is difficult to make any generalizations as to the economy, for each case must be considered separately. When mines have a power station already installed it is undoubtedly cheaper to adopt an electric hoist, even if it means an extension of the generating capacity, on account of the lower operating expenses and attendance, but whether it is better to have an equalizing system or not will depend on conditions. If the hoist is comparatively small possibly it will affect the total load very little. In the case of deep metal mines the hoisting load will usually be found to be quite a large proportion of the total, increasing with the depth. In order to obtain the benefits of an electric hoist in such a case, it is necessary to use some equalizing system to increase the load factor, and when this is done the hoisting cost per ton of material handled can be brought to a very low figure. When the costs of hoisting with a simple non-condensing steam plant and with an electric hoist are compared, the latter is undoubtedly the more economical, but when it is a question of using a modern compound condensing steam hoist with automatic cut off, a little more consideration is necessary. Under certain circumstances such a steam plant may have lower costs, but there are very few instances which, when properly investigated, do not show that the electric plant, if properly designed, is the more advantageous. In making comparisons care should be taken to avoid using any theoretical cycle as a basis, for the only true ground to work on is the actual duty over a considerable period, taking into consideration the time when the hoist is idle, as well as when it is running. With an ordinary plant the actual useful work done may be from 50 per cent to 75 per cent of the possible output, depending on the circumstances. This may be to the advantage of the electric plant or otherwise. The load factor of an electric plant is the ratio of the mean input to the maximum, and the effect on a generating plant will depend on the other power requirements and the load factor. If, for instance, the general load is 500 kw. and the load factor is 50 per cent, the generating capacity required is 1000 kw. The addition of a hoisting load of, say, 300 kw. with a load factor of 33 per cent will increase the required capacity to 1900 kw. and will reduce the load factor to 42 per cent. If, by means of an equalizing system, the hoisting load factor is brought up to 80 per cent, the total load factor will be 65 per cent. The cost of power with different load factors may be readily obtained if records are kept of the various items entering into the total. With a steam-oper-

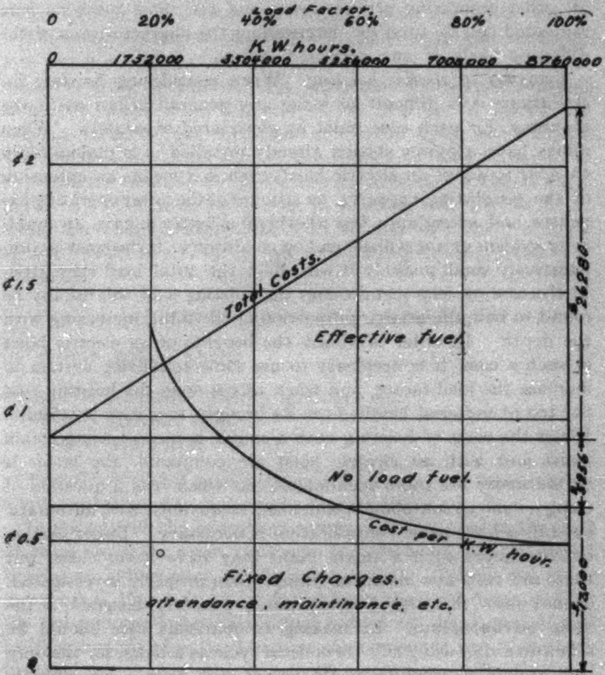

FIG. 10

ated generating plant the total cost will be made up of fuel, water, oil and waste, interest, depreciation, attendance, maintenance and repairs. Practically the first two are the only ones which vary with the load and a certain proportion of them is also constant. As an approximate guide, it may be considered that the fuel consumption when running idle will be about 20 per cent of the full load value and the water about the same. The remaining four-fifths will vary directly with the load so that we have a condition represented by Fig. 10. Suppose, for example, a plant of 1000 kw. capacity, the capital cost of which installed is $80 per kw., the coal consumption at full load being 2½ lb. per kw. hr., the cost being $3 per hr. With interest at 5 per cent and depreciation also 5 per cent and maintenance, stores and attendance at $5000 per year, the total fixed charges will be $13,000. Assuming that water is free, the coal required, running light or a basis of 24 hours per day, is about 1752 tons, which at $3 amounts to $5256 per year, making the total constant charges $18,250. The capacity of the plant when running at full load continuously will be 8,760,000 kw-hr. per year and the effective fuel required to produce this output is 8,760,000×2 = 17,520,000 lb. or 8760 tons, costing $26,280. This together with the fixed charges makes a total of $44,536, giving a cost per kw-hr. of 51c. With 50 per cent load factor the effective fuel consumption would be 4380 tons, costing $13,140, and the total running cost $31,396. The output would be 4,380,000 kw-hr. per year so that the cost per kw-hr. is 72c. In this way a curve may be readily plotted and it will show how a balancing system reduces the cost of power by increasing the load factor. The above method is not absolutely correct, since other factors enter into the running costs, but it is sufficiently close to enable a fairly accurate estimate to be made, for any particular case. In order to find the average load factor for the hoist the total consumption per trip must be taken as a basis. In the case of a balancing system the input may be considered as being made up of two parts, one being constant, representing the light running losses, and the other the total per trip minus this value. Supposing, for instance, that a plant is designed to equalize completely the load on the basis of 30 trips per hour, the input being 10 kw-hr. per trip and the light running losses of the motor generator set will be about 20 per cent of this figure, or 60 kw-hr. per hour. As designed, the load factor is 100 per cent, but if the average number of trips is 20 per hour the total consumption, instead of being 300 kw- hr. is $60+20\times 8=220$ kw- hr., and the load factor $\frac{220}{300}=0.73$. From the daily or weekly output the real load factor of the plant may be obtained in this way and the actual running costs may be ascertained. When dealing with a steam plant the same methods must be adopted and it will be found that the losses when the plant is idle are often very great, and, although on a certain definite cycle the running cost may be worked out to a figure which approaches that of the electric plant, the average economy might be very much lower. The actual power consumption of a well-designed electric plant with a motor generator equalizing set has been found from a great number of tests to be about 1.6 to 1.7 kw. per shaft horse power, and for a plain hoist without any equalizing system, about 1.25 kw. is a fair figure. When considering the running costs the transmission losses must be taken into account. With an electric plant the line losses will be as a rule small, but with a steam hoist the condensation in pipes, etc., is generally appreciable.

In conclusion, it may be well to draw attention to a few advantages of electric hoists from an operating standpoint. The most important is the complete control afforded over the hoist when running, enabling the operator to work much quicker and with greater certainty. The ease with which the braking can be taken care of electrically makes it possible to manipulate the hoist with the greatest precision, the mechanical brakes being used only for holding the load. Under certain circumstances energy may be returned to the system by the hoist, which reduces the power consumption, but the main point is that it obviates the excessive wear on the brakes which would otherwise have to absorb this energy. Electric hoists may be fitted with devices for automatically reducing the speed and preventing overwinding, which are absolutely certain in their action, and on this account the authorities in Germany allow men to be hoisted at a speed up to 2000 ft. per min., whereas, with steam hoists the limit is fixed at 1000 ft. per min. An electric motor is a very simple machine and requires considerably less attention than a steam engine needs, and the splendid service which it gives under the most severe conditions disposes of any question as to its reliability.

DISCUSSION ON "LARGE ELECTRIC HOISTING PLANTS", NEW YORK, MARCH 11, 1910

Edward J. Cheney: In connection with the torque diagram shown in Fig. 1 of his paper, Mr. Sykes gives a formula for computing the motor horse power. The evident intention of this is to reach the root-mean-square value of the cycle. This formula is not mathematically correct because the mean square of a sloping line is not one-half the sum of the squares of each end. The expression should be,

$$\text{(a)}\quad HP = \sqrt{\frac{\frac{HP_1^2+HP_2^2+HP_1HP_2}{3}\times t+\frac{HP_3^2+HP_4^2+HP_3HP_4}{3}\times t_1+\frac{HP_5^2+HP_6^2+HP_5HP_6}{3}\times t_2}{T_1}}$$

which holds good for all cycles, whereas the formula given in the paper is correct only for cycles with horizontal lines, such as Fig. 2, and is considerably in error where the lines have as much slope as in the usual hoisting cycle.

Ordinarily t and t_2 are small compared with t_1, and consequently $H\,P_1$ and $H\,P_2$ are nearly equal, and $H\,P_5$ and $H\,P_6$ are nearly equal, and the formula given above may be simplified without introducing any appreciable error, to the expression

$$\text{(b)}\quad HP = \sqrt{\frac{HP_a^2\times t+\frac{HP_3^2+HP_4^2+HP_3\,HP_4}{3}\times t_1+HP_b^2\times t_2}{T_1}}$$

where $H\,P_a = \dfrac{H\,P_1+H\,P_2}{2}$ and $H\,P_b = \dfrac{H\,P_5+H\,P_6}{2}$

After having found the correct root-mean-square value it does not follow that this should be the motor rating. As Mr. Sykes points out, the heat is not carried away at the same rate all the time, the reason being that at standstill and at the reduced speeds of acceleration and retardation, the ventilation is less than at full speed. Now a motor rating is ordinarily taken to mean the rating at which the motor will operate continuously at full speed with a given temperature rise, and apparently this is a very convenient basis and worth maintaining. In order to put hoist motors on this basis and make them comparable with other types they should have such a rating that when operated continuously at full speed at that rating they would have the same temperature rise as when operated on the normal hoisting cycle.

The root-mean-square value of the cycle as determined from the above formula must, therefore, be corrected by such a factor as shall represent the difference between the average dispersion of heat over the cycle and the dispersion of heat at full running speed. This factor depends upon the relative amount of time at reduced speeds, and also upon the relative importance of ventilation and conduction in cooling effect, and so upon motor speed and general design. It will be readily apparent that a high speed motor is more dependent upon ventilation than a slow speed motor, and the compactly built induction motor more than the comparatively open direct current motor.

The designer must, therefore, determine this factor in individual cases, but for a general approximation it may be taken that the cooling during acceleration and retardation is 75 per cent, and during standstill 50 per cent of that at full speed. From expression (**b**), we would then derive the following expression for the correct horse power rating of motor:

$$\text{(c)}\ H\,P=\sqrt{\frac{HP_a^2\times t+\dfrac{HP_3^2+HP_4^2+HP_3\,HP_4}{3}\times t_1+HP_b^2\times t_2}{.75\,t+t_1+.75\,t_2+.5\,t_3}}$$

where t_3 = time at standstill.

As the generator runs at nearly full speed all the time, no such correction need be made in its rating, and instead of being 10 per cent greater than the hoist motor, as stated by Mr. Sykes, it will very frequently be actually less. In a flywheel set, the motor of the set has no peaks to increase its heating, and so we may have the rather amusing case of a motor driving a generator of greater rating, which in turn supplies power to a motor of still greater rating. Apparently in such cases the efficiency has somehow become reversed, but really the ratings are perfectly logical when properly viewed.

In considering the converter equalizer as compared with the Ilgner system, it must be admitted that in the latter, the flywheel set transforms all the power, while in the former, the flywheel set only transforms the fluctuations above the mean. It must, however, be borne in mind that in the Ilgner system, the power is only transformed once, while in the other system, the excess power must be taken through the transformers, converter and equalizer to the flywheel and, later on, taken back again in reverse order to the line. With very peaked cycles, such as we usually have, this means that the converter and equalizer are not so small compared with a motor generator set. The flywheel must store more energy in the converter system, because the rheostatic losses of the induction hoist motor add to the peak. Taking these facts into consideration, and after a careful comparison of the two systems under various conditions, we must take exception to Mr. Sykes' statement that the converter system is the cheapest to install.

As Mr. Sykes points out, the rheostatic losses of the induction hoist motor with the converter system must be balanced against the losses in the slip regulator of the Ilgner system. Here, also a comparison of typical cycles will show the Ilgner system to have the advantage. The real argument in favor of the converter equalizer system seems to be the fact that the hoist is not dependent upon the flywheel set, and even this fails when the generating station is too small to handle the hoist without a balancing system. The converter system also has some advantages where more than one hoist is to be equalized, but where several hoists are operated the diversity factor may be depended upon to smooth out the line load, and a balancing set is hardly necessary.

A paper presented at the 245th meeting of the American Institute of Electrical Engineers, New York, March 11, 1910.

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TESTS OF AN ILGNER ELECTRIC HOIST

BY R. R. SEEBER

In the copper mining district of northern Michigan a fair-sized mine usually operates two or more shafts along the strike of the lode, these shafts being usually at least a thousand feet apart. The tonnage to be hoisted from each shaft is large, —from 13,000 to 25,000 tons per month. The hoisting engines used are generally steam-driven, non-condensing, duplex engines with Corliss valves, supplied by steam from separate boiler plants where the distance between shafts is great.

In an attempt to centralize power plants and secure central station economies, the Winona Copper Company installed an electric hoist of the Ilgner type, with Ward Leonard control. A brief description of this plant appeared in the *Engineering and Mining Journal* of July 19th, 1909 . The only point of variation from the simple Ilgner set lies in the connection of two generators to a single induction motor by flexible couplings. These generators serve motors which operate hoisting drums at separate shafts viz. No. 4 shaft Winona, and No. 1 shaft, King Philip. The hoist for No. 4 shaft is about 1,700 ft. from the power plant and in this building the motor-generator set is placed. No. 1 King Philip hoist is 1,500 ft. from the motor-generator set. The equipment of the motor-generator set is as follows:

In the middle of the set is a 12-pole, 450 h.p, 600-rev. per. min. 2,080-volt, three-phase, 60-cycle, variable-speed, induction motor, connected on each side to a 20-ton flywheel which is 10 ft. in diameter, and to a 6-pole, 170-kw, 575-volt, interpole, direct-current generator. On each side of the shaft is placed a separate exciter which delivers current at 125 volts. The lubrication of the four main bearings that support the flywheels and direct-current generators is supplied by two sets of oil pumps, belt-driven from the shaft.

The hoist motors are 6-pole, 200-h.p., 430-rev. per. min. 550-volt motors, and are shunt-wound. The fields, both of this motor and the direct-current generators are excited by current from the exciter on the motor-generator set, which is kept at a constant voltage of 125 by voltage regulators. The current in the hoist motors is varied and reversed through controllers of the usual railway type, placed in the field circuit of the generators. The first point on the controller operates a contactor which closes the main circuit from the generator to the motor.

The alternating current for operating the motor-generator passes through a regulator which automatically varies the resistance in the rotor of the motor-generator set in proportion to the demand of the motor for current.

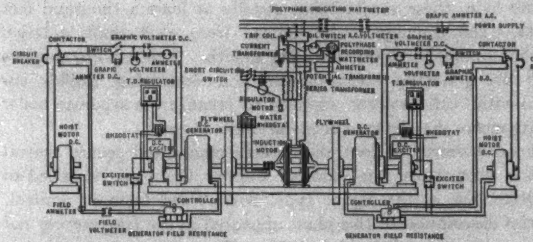
POLYPHASE INDICATING WATTMETER
GRAPHIC AMMETER A.C.
POWER SUPPLY
CONTACTOR
GRAPHIC VOLTMETER D.C.
CIRCUIT BREAKER
SWITCH
GRAPIC AMMETER D.C.
VOLTMETER
AMMETER
T.D.REGULATOR
SHORT CIRCUIT SWITCH
TRIP COIL
CURRENT TRANSFORMER
OIL SWITCH
A.C.VOLTMETER
POLYPHASE RECORDING WATTMETER
AMMETER
POTENTIAL TRANSFORMER
SERIES TRANSFORMER
REGULATOR MOTOR
WATER RHEOSTAT
INDUCTION MOTOR
FLYWHEEL
D.C. GENERATOR
RHEOSTAT
D.C. EXCITER
HOIST MOTOR D.C.
EXCITER SWITCH
CONTROLLER
FIELD AMMETER
FIELD VOLTMETER
GENERATOR FIELD RESISTANCE
GRAPHIC VOLTMETER D.C.
CONTACTOR
CIRCUIT BREAKER
AMMETER
VOLTMETER
GRAPHIC AMMETER D.C.
T.D.REGULATOR
FLYWHEEL
D.C. GENERATOR
RHEOSTAT
D.C. EXCITER
HOIST MOTOR D.C.
EXCITER SWITCH
CONTROLLER
GENERATOR FIELD RESISTANCE

FIG. 1.—Diagram of connections of motor-generator set

During February, 1910, detailed tests of this set were made to determine the performance under varying conditions, and to procure coal-to-rock ratios to compare with ratios for steam hoists under similar conditions.

On the switchboard controlling the set, the following instruments were already installed:

Alternating current indicating ammeter.
Recording wattmeter.
Direct-current ammeter and voltmeter for each direct current generator.

In addition for the purposes of this test, the following instruments were installed, as shown on the diagram Fig. 1:

Two 600-0-600 direct current graphic voltmeters, one in each generator circuit.

Two 800-0-80 direct current graphic ammeters, one in each generator circuit.
One 125-ampere alternating current graphic ammeter.
One 125-volt direct current indicating voltmeter.
One 100-ampere direct current indicating ammeter.
One indicating wattmeter with necessary current transformers.
One 600-rev. per min. tachometer.

No. 4 shaft Winona is served by the hoist drum in the same building as the motor-generator set. This is an old duplex steam hoist, with the cranks disconnected. The motor drives the old crank shaft through gearing. The drum is seven ft. in diameter and holds 1,500 ft. of rope. The rope is 1⅛ in. in diameter and weighs two lb. per ft. No. 4 shaft is double-compartment and the skips work in balance. Because at present very little hoisting is being done in this shaft, only the south skip is used for loads and the north skip carries 2,100 lb. of rock to lessen the starting moment. At the time of the test the north skip had filled with ice, so that the total counterbalancing weight was 3,300 lb. This caused more power to be used for the lowering of the south skip than for hoisting it. The loaded skip weighed 5,400 lb. Of this amount, 3,300 lb. is counterbalanced leaving only 2,100 lb. of rock and the hoisting rope as the net load.

No. 1 shaft King Philip is operated by an old geared steam hoist, with the cranks disconnected and the crankshaft geared to the motor in the same manner as at No. 4 Winona. The drum is five ft. in diameter and holds 1,200 ft. of one-inch rope, weighing 1.58 lb. per ft. The shaft is built with two compartments but only one skip is running, leaving the hoist unbalanced.

The skips in both shafts are the same and weigh 2,900 lb. each. Each holds 2.7 tons of rock when full. The test was conducted under normal working conditions and the loads varied. During the time of test, a man was stationed at the brace of each shaft to observe the fulness of the skips. The average distance of the rock from the top of the skip was estimated for each load and a correction was applied.

The work at present being done at these shafts is comparatively small, because only development work is under way. Since all reliable information that I had concerning the operation of steam hoists was at a hoisting rate of 12,000 to 15,000 tons per month, we arranged to hoist from each shaft for an hour at near this rate. During all this time the curve-drawing instruments were in operation and gave accurate records of each operation. Readings of the alternating-current wattmeter, voltmeter, and ammeter were taken every five seconds. The starting and stopping time of each of the hoist movements was taken, and the nature of the load recorded. The speed of the motor generator set was taken at regular intervals.

The following tabulations show the levels from which rock was hoisted during this one-hour test, also the total number of skips, total rock hoisted from each level, the average load, the distance from the level to the dump on the incline of the shaft, 70 deg. and the product of load and distances; also totals and averages. This rate of hoisting corresponds to about 19,000 tons per month or rather more than the rate of the steam hoists with which it is compared.

WINONA SHAFT

Level	Skips	Load		Distance	Load distance
		Tons	Average		
9th	5	11.9	2.4	918 ft.	10924
10th	4	10.2	2.5	1018 ft.	10384
11th	4	10.2	2.5	1118 ft.	11403
12th	3	7.7	2.6	1218 ft.	9379
	16	40		1052 ft.	42090 At 600 ft. equivalent to 70.15 tons

KING PHILIP SHAFT

Level	Skips	Average load		Distance	Load-distance
		Tons	Average		
5th	1	2.0	2.0	425′	850
6th	6	13.2	2.2	524′	6917
7th	—	—	—	623′	—
8th	5	10.2	2.04	729′	7436
9th	3	4.95	1.65	832′	4119
10th	4	9.45	2.36	932′	8807
11th	—	—	—	1034′	—
12th	3	7.4	2.5	1135′	8399
—	22	47.2	2.15	Average 774	36528 At 600′ equivalent to 60.88 tons

Adding the total tons hoisted at Winona to the total tons hoisted at King Philip during the same period gives an equivalent of 131 tons hoisted from a depth of 600 feet in a 70-deg. incline. The total kilowatt-hours taken by the motor-generator set during this hour was 211. This output was determined by reading an indicating wattmeter every five seconds and taking the average. The power necessary to hoist one net ton of rock from a depth of 600 ft. on the incline was 1.61 kw-hr.

Tests of our power plant, under present light-load conditions, have shown that it requires about four pounds of coal to produce one kilowatt-hour delivered on the switch board of the motor-generator set. The amount of coal required to hoist a ton from this distance is therefore 6.44 lb. giving a coal-to-rock ratio of 1 to 310.

Winona	70.15 tons
King Philip	60.88 "
	131.03 " hoisted at 600 ft. depth on 70 deg.

211 kw-hr. taken by set.
1.61 kw-hr. per ton.
6.44 lb. coal per ton at 4 lb. coal per kw-hr.
Coal-to-rock ratio = 1 to 310.

For purposes of comparison with the steam hoist conditions, I have tabulated the results in rock hoisted and kilowatt-hours taken by the motor-generator set for an average day.

16 hours 211 kw. = 3,376 kw-hr.
4 " 80 kw. = 320 "
1 hour 55 kw. = 55 "

Total of 3,751 kw-hr.
3 hours shut down.
Total of 24 hours.

Rock is hoisted during but 16 hours of the time, making the total rock hoisted for both shifts 2,096 tons; or 1.79 kw. hr. are required to hoist one net ton of rock from a depth of 600 ft. on a 70 deg. incline. This makes the coal-to-rock ratio for the above conditions 1 to 279.

The theoretical value of kilowatt-hours per ton hoisted taken from Fig. 21 of the paper presented by Messrs. Rushmore and Pauly* is 1.7 kw-hr. Taken from the curves in Fig. 22 for the 8,000-ft. hoist, this value is 1.55 kw-hr.

At the D shaft of the Champion Copper Company, a 24-in. by 60-in. duplex Corliss engine operates a double conical hoist drum. The shaft inclination is about 70 deg. the skips working in balance. The boiler plant supplies the rock house engine and dry in addition to supplying the hoist. For the first four days of November, 1905, the boiler plant supplied the hoist alone. The coal-to-rock ratio for these four days, at 600 ft. average depth, was 1 to 154. Using a percentage of fuel burned for the rock hoisted, obtained from results of this four days' test (68.4 per cent to hoist), the ratio for the remainder of November was 1 to 185, showing gain by better boiler load. For December of the same year on the same basis, the ratio was 1 to 166. The average load of rock was 2.1 tons, the total amount hoisted in a month being about 15,000 tons.

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* A. I. E. E. TRANSACTIONS, 1910, page 284.

At the Winona mine, No. 3 shaft was operated in June, 1907, by a separately-fired boiler plant. The hoist is a duplex geared hoist with a rolling valve. The shaft is inclined 70 deg. from the horizontal and the skips work in balance. The average load of rock was about 2.1 tons. In June, the coal-to-rock ratio at 600 ft. depth. figured as before, was 1 to 124. In August and September, 1907, this hoist was supplied from a larger plant, the hoist being 15 to 20 per cent of the whole load. The distribution of coal which we made gives a ratio of 175 to 200.

The following tabulation compares these ratios:

Electric hoist, two shafts, Winona; coal-to-rock ratio 1 to 279.
Champion *D* hoist; steam (alone); coal-to-rock ratio 1 to 154.
Champion *D* hoist, with rockhouse; coal-to-rock ratio 1 to 185.
Winona No. 3 hoist, steam (alone); coal-to-rock ratio 1 to 124.
Winona No. 3 hoist, steam, (central plant)—coal-to-rock ratio 1 to 175, to 1 to 200.

I feel satisfied from these figures that, even with steam generated in a central plant, a coal-to-rock ratio of 1 to 200 is about all that can be expected from steam hoists of this type, under the given conditions. This shows a coal saving by the electric method of 25 per cent over the steam method.

Fig. 2 shows the operation of the motor-generator set and both hoist motors for a typical section of about nine minutes length, taken from the one-hour test. The curves here shown will serve to describe most of the operation. The top curve shows the alternating current input plotted from five-second readings of the indicating wattmeter. The average for the nine minutes is 208.25 kw. or slightly below the average input for the hour.

The second curve shows the speed of the motor generator set, the extreme variation being from 440 to 480 rev. per. min. during this period.

The next three curves show the volts, amperes, and kilowatts output of the direct-current generator driving the No. 1 King Philip motor.

The last three curves show the volts, amperes, and kilowatts output of the direct-current generator driving the Winona No 4 hoist for the same period.

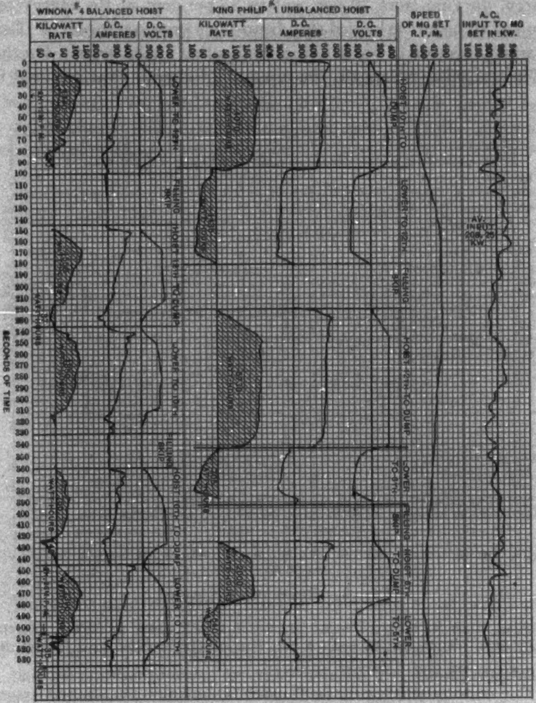

FIG. 2.—Operation of motor-generator set

Where electricity is used for hoisting, the main reason for using an Ilgner fly-wheel set is to take the peak loads off the power station. How well this is accomplished is shown by comparing the input curve of the diagram with the two curves of direct-current output. Incidentally this method utilizes the energy of a descending unbalanced skip, the motor acting as a generator and restoring energy in the flywheel. For the King Philip hoist, unbalanced, the amount thus restored is comparatively large, varying from 20 per cent to 35 per cent of the energy required to hoist the loaded skip from the corresponding level. This variation is due to variation in the loading of the skips. On the Winona hoist, balanced, the amount of energy thus restored is

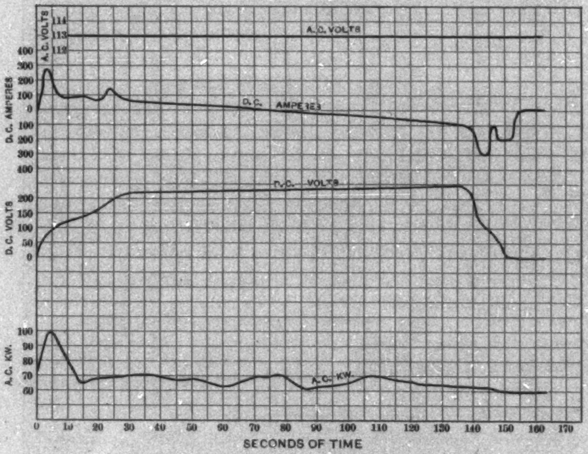

FIG. 3.—Restoration of energy

very small and occurs only when the motor is used as a brake at the close of the hoisting period.

The restored energy for both cases is shown on the shaded areas below the line. An interesting example of this restoring action is shown (Fig. 3) on Winona No. 4 hoist, where men are being hoisted on the south skip. Energy is required at starting but the demand gradually decreases and at about the 8th level the weight of the descending north skip counterbalances the ascending skip. During the remainder of the hoisting period energy is being stored in the flywheel.

Where a double compartment shaft can be used and the skip and rope can be counterbalanced by duplicates in the other compartment, the counterbalancing skip being ready for a paying load on reaching the bottom, it is obviously not economy of power to use any other system of restoring the energy of the descending skip. The efficiency of any other system will be very low compared to the efficiency of the counterbalancing skip where the only losses are friction and air resistance.

Fig. 4 shows the current output of the King Philip generator when hoisting a full skip from the 12th level, and the energy restored to the set when lowering the same skip still full. This was done twice, as shown.

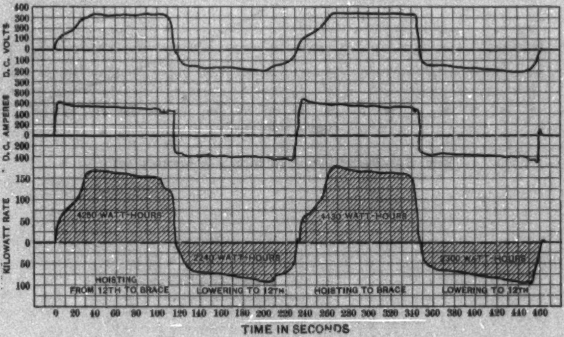

FIG. 4.—Energy expended in hoisting and lowering unbalanced hoist

The watts used in hoisting the first time were 4,250; watts returned lowering were 2,243, showing an efficiency of restoration of 52.8 per cent. The watts used hoisting the second time were 4,430; the number of watts returned lowering the second time was 2,300, showing an efficiency of restoration of 51.9 per cent.

Fig. 5 shows the decreasing speed of the motor generator set, after the power is shut off on Saturday nights. About three hours are required for the set to come to rest.

Fig. 6 shows the acceleration of the skip and the rope speed for the hoisting period.

The greatest disadvantage of the Ilgner system is a constant loss in windage and bearing friction of the motor-generator set

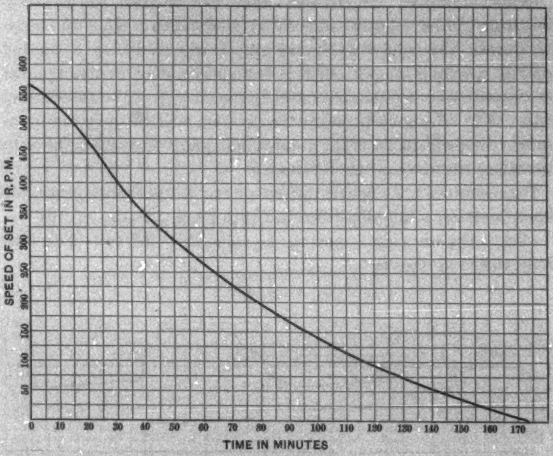

FIG. 5.—Retardation of motor-generator set

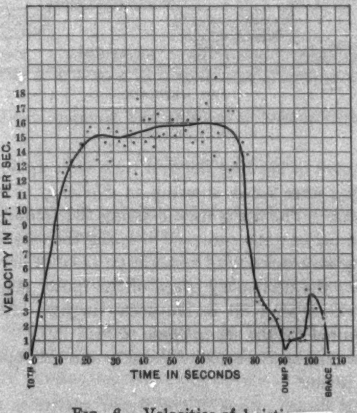

FIG. 6.—Velocities of hoisting

itself. Observations have shown this loss for the set at this plant to be very nearly 55 kw. This loss can be reduced materially by casing the flywheels. When the work done by the hoist is large enough to make the proportion of this constant loss small, an Ilgner flywheel set adds fuel saving to the saving of labor, etc., due to the centralization of the power plant.

The use of this system enables us to dispense with two boiler plants and their firemen. It would have been necessary, also to build larger boiler plants, with railroads and coal trestles to serve them. The hoists themselves handle the skips much better than the steam hoists, starting from rest very smoothly. The large amount of repair work necessary on a reciprocating engine is also done away with.

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THE GENERATING SYSTEM OF AN ELECTRIC LIGHTING COMPANY

BY A. R. CHEYNEY

Under this head it is intended to touch briefly upon a few of the important considerations which may be of general interest relating to the production of electricity. The generating system here spoken of includes everything from the coal at the mine to the outgoing wires from the substations.

The main function of a lighting company is to sell electricity, and in order that it may meet with the success to which it is entitled, two facts must be kept in mind. The generating cost must be kept as low as possible, and the service must be supplied at a uniform pressure, and absolutely without interruption. Two elements are involved in the solution of the problem of cost and reliability; the physical, which follows certain fixed and unalterable laws; and, closely interwoven, the human element, as vital and as far reaching as the physical itself. This close relationship between things material and the human element is a condition that the operator has always with him, and it is most important that his conception of both be kept clear and separate.

Fig. 1 shows in graphic form some of the various details of a generating system and their relative interdependence. From the coal supply at the mine to the wires leaving the substation, one continuous, unbroken chain binds all the parts together The failure of a single link unless properly cared for, may mean the failure of all. Accident to any one of a certain class of the above composite parts may involve the system in difficulty almost instantly, as, for instance, failure of electrical machinery, underground cables, oil switches, etc. Other parts may fail

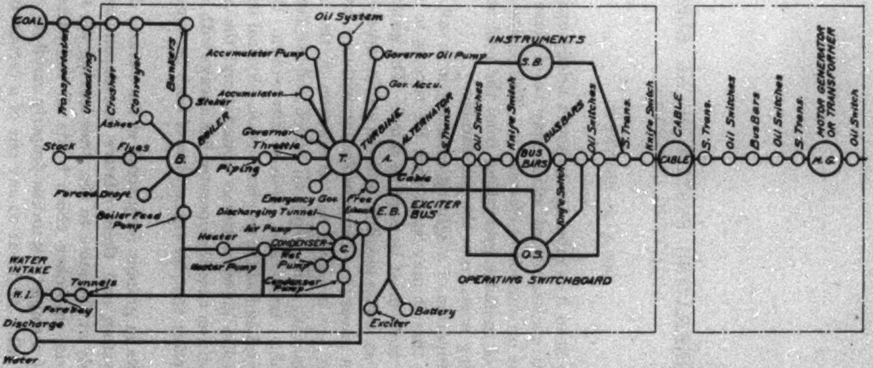
COAL
Transportation
Unloading
Crusher
Conveyor
Bunkers
Stoker
Ashes
Stack
Flues
B.
BOILER
Forced Draft
Boiler Feed Pump
Piping
Throttle
Governor
Accumulator
Accumulator Pump
Oil System
Governor Oil Pump
Gov. Accu.
T.
TURBINE
Emergency Gov.
Free Exhaust
Discharging Tunnel
Air Pump
Heater
CONDENSER
C.
Wet Pump
Heater Pump
Condenser Pump
WATER INTAKE
W.I.
Tunnels
Forebay
Discharge
Water
A.
ALTERNATOR
Cable
E.B.
EXCITER BUS
Exciter
Battery
S.Trans.
Oil Switches
Knife Switch
BUS BARS
BUS BARS
Knife Switch
Oil Switches
S.B.
INSTRUMENTS
O.S.
OPERATING SWITCHBOARD
S. Trans.
Knife Switch
CABLE
CABLE
S. Trans.
Oil Switches
Bus Bars
Oil Switches
S. Trans.
M.G.
MOTOR GENERATOR OR TRANSFORMER
Oil Switch

FIG. 1—Diagramatic scheme of connections of generating plant equipment.

and the system will continue to operate for a certain period, and before the danger point is reached repairs may be effected.

In any case, a break anywhere along the line must be immediately cared for. This, with large and heavy machinery, is a different proposition from the repairs to the small plant of a few years ago. Everything, including even many of the wrenches, has to be carried by the traveling crane, which, as a rule, has two hoists, in this instance one of 60 tons, and one of five tons for more rapid manipulation. As it requires a considerable length of time to have repair parts made up, in the case of our large units, it is necessary to keep on hand spare parts to a certain limited extent, at least, in order that the prolonged disablement of a main generating unit of large size may be avoided as far as possible.

If we consider the above diagram to be made out in duplicate or triplicate, properly cross connected, it will readily be seen that the stability of the system is greatly increased. This is what actually takes place in modern central station construction. Certain of the links, such as coal supply, water supply, main station bus bars, etc., as a rule, constitute single links and are depended upon for absolute freedom from trouble.

The best of our modern plants, operating under the most favorable conditions as to load factor, with steam turbines of the latest type, mechanical stokers and superheated steam, delivers about 12 per cent of the energy in the coal to the bus bars. From this must be subtracted the loss in transmission and transformation. The most efficient light known can actually make use of but about 10 per cent of this resultant energy within the range of the visible spectrum, so that we are actually converting into light but about one per cent of the energy in the coal. The efficiency of the electric motor is, of course, higher, in which case our total efficiency would reach possibly eight or even nine per cent.

The matter of load factor, as it affects the generating system, is so radically different in the cases of the gas plant and the electric plant that it is difficult to find enough in common to afford any comparisons. In the gas system, generators may be operated at maximum economy, storing the gas all the while until the demand is made for it. There is, unfortunately, no such thing as storing any small part, even, of the output of a modern central station, other than in the revolving energy of the wheels themselves.

Modern generating systems are all polyphase, and in our large cities the safe limiting voltage is fixed by the insulation resistance of the underground system. It is, of course, advantageous to have a voltage as high as possible, especially when the energy has to be transmitted to considerable distances. An underground cable that can safely carry 1,800 kw. at 6,000 volts is capable of carrying over 3,000 kw. at 11,000 volts. As the expense of the underground cable system is very heavy, this factor must be very carefully balanced against the other factor of the problem, that of absolute safety, if such a thing may be said to exist. Thus, various engineers and companies use different voltages. The Manhattan Company at 11,000 volts operates side by side with the New York Edison Company which uses 6,600 volts. The Commonwealth Company, of Chicago, operates at 9,000 volts, the Philadelphia Rapid Transit Company at 13,000 volts, and the Philadelphia Electric Company at 6,000 volts.

The elements which have most to do with the main station cost are fixed charges, maintenance expense, coal, and labor. Both the fixed and maintenance charges are practically established with the design and construction of the plant. The items of coal and labor, therefore, are the most important of those items which may be affected by proper or improper operating methods, and are the chief factors in determining the generating cost, which, in this case, is taken to include the total cost of the main and substation system. The thermal efficiency of a plant burning a high grade of coal does not differ greatly from that of a plant burning a lower grade, provided both plants are properly designed and operated. If, now, in one station we can deliver, coal to the fire room at $1.00 per ton and in another station it costs $3.00 per ton, uniform excellence of design being assumed, the second station cannot approach the first in generating cost.

While this cost does not by any means fix the selling cost, it is in all cases important, and, where energy is purchased in large blocks, one of the deciding factors. The relation of the generating to the selling cost is clearly shown in published reports of the Boston Edison Company, for the year ending June 30, 1909, filed with the Massachusetts Gas and Electric Commission. (*Electrical World*, September 30, 1909). This is probably a fair example of an average large central station system selling current for both lighting and power. The following table will illustrate the above relationship.

Item	Per cent of total cost
Manufacturing cost	24.60
Purchased electricity	0.02
Distribution cost	15.65
Office expenses, management, etc	15.65
Miscellaneous taxes, insurance fund charges	44.00
	100.00

Further information with regard to the above system might be of interest.

Kw-hr. generated during the year	90,877,123
Kw-hr. sold during the year	62,177,318
Ratio of energy sold to energy generated	68.5 per cent
Coal consumed	95,350 tons, or 2.35 lb. per kw-hr.

The total expense is 12.5 per cent of the total capitalization. The manufacturing cost including main and substations, which is 24.6 per cent of the total cost is subdivided as follows:

MANUFACTURING COST, MAIN AND SUBSTATIONS

Item	Per cent of total cost
Fuel	12.50
Rentals, real estate	0.80
Oil and waste	0.19
Wages at stations	6.18
Water	0.70
Station repairs	0.37
Steam plant repairs	2.11
Electrical plant repairs	1.74
	24.60

It must, of course, be understood that local conditions affect most materially the matter of relative costs. The possibility of reducing certain items of expense or of eliminating them altogether, such as office expense, metering and collecting, etc., has been carefully considered by central station men, and one solution is exemplified in the very low cost to street railway companies, which is given by the Commonwealth Edison Company, of Chicago, which has figured out that with careful engineering a lighting company can depend upon the increase of load factor brought about by a combination of lighting and railway loads to establish a profitable safe selling price below that at which a single plant for either lighting or railway purposes alone could generate it. The price given in the case of certain railway load carried by the Commonwealth Company, as published, is 0.5 cent per kw-hr. plus $15.00 per kw. of maximum demand during the year, sold at the main station bus-bars.

The design and construction of any system is one of the important factors in determining the generating cost. These elements also enter very materially into the question of reliability. It is impossible for a plant of inferior design or construction to compete with one well designed, and efforts made to overcome this constant drawback by more careful and systematic operating methods are always accompanied by increased cost and possibly by chance of interruption of service. Machinery should be installed with due regard to its probable life in service. Any defective or uneconomical machinery should be discarded. A shut-down in a large system is a dear price to pay for the relatively small saving caused by retaining such machinery.

One noticeable feature in the latest station practice would seem to be the introduction of the steam turbine, not only in the case of the main generating units of the plant, but in connection with auxiliary apparatus, such as boiler feed pumps etc. The added simplicity, great reduction in space required and also the fact that these small units combine the facility of handling of the motor-driven with the reliability of the steam-driven auxiliaries, and also that they are fairly economical in the use of steam, goes far towards recommending them for such purposes. They may be operated condensing or non-condensing as required. The steam curve of a certain 90-h.p., high-pressure turbine, using steam at 175 lb. pressure, shows, at full load, 34 lb. of steam per hour, at three-quarters load, 37½ lb., and at half load, 45 lb.

One item which should be carefully considered when any plant is projected is that there should be incorporated in its design provision for periodic testing, for measuring the steam taken by the auxiliaries, for instance, in more or less detail, for running boiler tests, etc. Without this provision, necessary changes in piping and connections in preparation for such a test involve such a considerable amount of labor and annoyance that it is quite probable that little actual testing will be carried on. In any event, the cost of conducting experimental investigations under such conditions will go far towards defeating the very purposes of the tests.

Testing may be made easy, convenient and practical. The fundamental measurements which are necessary are, of course, the weight of coal and water consumed, and the electrical measurement of the station output. The readings of the main output meters of the station should be carefully watched and the instruments regularly checked. In this connection it is important that, if possible, the instruments be checked with their respective series transformers in place. Thermometers should be installed at all important points such as in the steam lines, boiler feed lines, and in connection with the condenser equipment. The absence of proper installation for testing purposes, whether omitted for the sake of simplicity or otherwise, makes it impossible to obtain the best results.

In our modern stations we note that this matter is being very carefully considered, and provision made so that all such investigations may be conducted at a minimum of trouble and expense. The operation of a properly designed modern station thus becomes, in itself, a constant succession of tests. Regular and periodic records are kept covering the items, the information contained in these records being at times very valuable.

Several items incident to economical operation might here be mentioned. The amount of blow-off leakage should be weighed at stated intervals. The blowing down of boilers should also be carefully recorded and should find its place in the analysis of heat losses. Losses due to mechanical inefficiency of auxiliaries should be reduced wherever possible. These become a constant drain on the station, even though at times the excess of exhaust steam is necessary to heat the feed water. It is advisable, therefore, to use high efficiency auxiliaries, mostly steam driven, and, if more steam is needed at times of peak load, or even regularly during the day, to obtain it from other sources, for instance, the second-stage pressure of the steam turbine units may be made use of.

It should be observed that whatever steam is admitted to the heaters should be actually utilized therein. This means that the heaters themselves must be properly cared for and kept in an efficient condition. Exhaust piping should be carefully covered in order to prevent condensation before the steam is returned to the heaters. The condensation of the main steam lines should be known, and occasionally, if possible, it may be advisable to make a test to keep a check upon it. The firing of soft coal is best cared for by stokers, by which means regular and efficient combustion can be maintained, the smoke nuisance is eliminated, and a saving both of coal and of labor, is accomplished. Flue gas analysis is, of course, necessary. The best method of taking samples and of analyzing is still subject to a divergence of opinion. The method of obtaining an integrated sample over an eight hour run on a boiler, or three samples per 24 hours, seems to offer many advantages. The ashes should be carefully weighed and a regular analysis made to indicate the proportion of combustible matter thrown away unconsumed. Every effort should be made to reduce this waste to the minimum and herein is an opportunity for considerable saving in very many plants.

Careful attention must be paid to loading up of the main generating units, and the same applies to the substation machinery. It is frequently good practice to put the next incoming machine on the line rather early, in the case of a rising load, and to take it off early in the case of a load which is going down.

Load factors are more directly affected by the commercial than the engineering departments of the company, yet the question of load factor is vitally important in its effect on station cost. Sufficient men and machinery must be provided to care for the maximum possible load for the day. A thunder storm may raise the load by as much as 100 per cent or more. Boilers cannot be started up at a moments notice nor can auxiliaries or main generating units. It is, therefore, advantageous to install boilers that can be operated economically over wide ranges of load. The saving possible by thus reducing the banked fire losses is considerable. If boilers and other machinery be operated at 100 per cent over rating, it is evident that the machinery in commission could be reduced fully one half in very many instances.

As an example of the above, two specific cases were taken in one of which the boilers were operated so as to carry the peak load of the station at normal rating, and in the other case the boilers were pushed at 100 per cent over rating on the peaks, an additional boiler being carried along as a reserve. The figures representing the coal used under the above conditions are as follows:

CASE 1. Boilers at rating. Total coal burned 210 tons, of which 35 tons were used on banked fires, leaving 175 tons actually consumed in producing steam.

CASE 2. Total coal consumed 181 tons, of which banked fires consumed 11 tons, while 170 tons were used in producing steam. In this particular instance, therefore, a saving of 29 tons, or 13 per cent, in fuel is obtained by pushing the boilers as above stated.

One of the great advantages of certain stokers over hand-fired furnaces under large boilers is the fact that the stokers can continue to operate at heavy overloads for a considerable length of time, whereas, as a rule, firemen cannot be depended on under such conditions except for very limited periods.

To illustrate the load that can be safely carried on a good boiler and to show the advantage of being able to operate a boiler at 100 per cent over rating still more plainly; consider a standard 630-h.p. boiler having 6,300 sq. ft. of heating surface and evaporating 21,750 lb. of water from and at 212 deg. fahr. per hour, or 3.45 lb. per sq. ft. of heating surface per hour. Assuming 20 lb. of water per kw. of plant output, the boiler would carry, at normal rating, a station load of 1,087.5 kw., while at 100 per cent over rating, which, as tests have shown, is not at all impossible under proper conditions, one 630-h.p. boiler would carry a load of 2,175 kw. Figuring from the factors of evaporation, assuming the feed water was being supplied at 180 deg. fahr., and that the boiler was delivering saturated steam at 175 lb. pressure, at 100 per cent over rating, and taking 2,175 kw. as the starting point, we find that by shutting down temporarily on the feed water, or in other words, resorting to the procedure well-known to all engineers of carrying water high up to peak, and leaving the peak with water slightly lower than normal, we can get an output from this same boiler from the energy stored in its own drums in the form of highly heated water, of 19½ per cent additional, or a total of 2,599 kw. This is not given as advocating the practice above mentioned, although without doubt it has probably saved more than one plant from a shut-down. The practice may be a dangerous one in a large plant. The point is, if such an increase in boiler output can be obtained by this means, it is one of the factors to be considered in the designing of our new boilers.

It is hoped, however, that the necessity for this procedure may never exist when the ideal station boiler is designed. Very many tests have been made on boilers at over rating in which very high efficiencies have been reached over wide ranges of load. In one instance at hand, a water tube boiler was operated at from 130 per cent to 190 per cent of rating with a very slight drop in efficiency.

Two factors entering seriously into the problem of reliability are the necessity for an interrupted coal supply, and also an ample supply of water for the condensers and the boiler feed pumps without chance of interruption, at all seasons of the year, and under all river and tide conditions. The lack of proper water supply is one of the reasons why the culm banks of our state have not been put to further use. The amount of water necessary in a plant of 50,000 kw., assuming 20 lb. per kw. and, in summer, 50 lb. per lb. of steam condensed, would be 50,000 ×20×50 = 50,000,000 pounds of water per hour.

The variation in temperature of water used for condensing, due to change in seasons is considerable. Thus, not only is a very much larger amount of water necessary at certain seasons than at others, in order to obtain high vacua, but circulating pumps must be installed either in duplicate, or adapted to variable speeds, in order to care for this condition. The average temperature of the water taken from the Schuylkill River for the past year was as follows:

1909	Monthly average	
January	37 deg. fahr.	
February	40 " "	
March	43 " "	
April	54 " "	
May	64 " "	
June	74 " "	
July	80 " "	
August	79 " "	
September	75 " "	
October	64 " "	
November	53 " "	
December	38 " "	
Highest temperature	84.4 deg. fahr.	July 2, 1909
Lowest temperature	34.2 " "	February 2, 1909

Every station should have worked out and kept in a conspicuous position—for instance, framed and hung over the desks of the chief operating men—a standard table of heat losses covering the best results that could reasonably be expected from the plant under the most favorable of conditions. This would then become an encouragement to endeavor to reach in practice the limits which theory has established. A plant operating without any detail knowledge of its heat expenditures works under a great handicap. Many of the items of heat expenditure are easily obtained. They are of very great assistance in reducing unnecessary plant losses. The following comparison between the results obtained in the large turbine station of the Commonwealth Company, of Chicago, and the reciprocating plant of the Interboro Rapid Transit Co., of New York, both of which sets of figures have been published at length and frequently quoted, is of interest.

	Commonwealth Co.	Interboro R. T. Co.
	Boiler Room Losses	
Refuse in ash pit	3.0	2.4
Rejected to stack	19.6	22.7
Radiation and unaccounted for	8.0	8.0
Banking fires	5.6	
	Engine Room Losses	
Rejected to condenser	48.1	60.1
Total boiler room losses	36.2	
Total turbine room losses	51.8	
Delivered to bus bars	12.0	10.3

We note in the turbine plant that the percentage of total heat rejected to the condenser is much lower than that in the reciprocating plant, the figures being 48.1 and 60.1 respectively. This would indicate, with equivalent boiler conditions, a greater mechanical efficiency for the turbine than for the reciprocating unit. This suggests the condensing equipment. It is extremely important that the condenser installed be of the highest possible efficiency and also that it be capable of producing a high vacuum at the time of peak load on the station in order that the boiler output may be reduced to the smallest amount possible at that time. The differences in temperatures between the exhaust of the main generating unit and the discharge water of the condenser should be as low as possible.

It frequently becomes necessary to depart slightly from conditions of maximum economy in order to give proper insurance of uninterrupted service. Under no conditions can we afford a general station shut-down. It is, therefore, generally necessary during the day and up until after the evening peak, say 11 o'clock at night, to have always available on the line an extra generator in the main station. This, in a turbine plant, is very easily accomplished by bringing up a machine to full speed, synchronizing and throwing it on the line. Closing the throttle valves then gives a machine as a motor ready for instant service merely by opening the steam valve. Steam saved by thus operating the turbine is considerable, as the remaining units may be kept at full load. It is, of course, necessary that the turbine should be allowed sufficient steam at certain intervals to keep it warm.

A first reserve unit in addition to those kept on the line, is always kept in readiness, as far as possible, with oil turned on and the condenser pump in operation ready for turning over of the main unit at a moment's notice. With regard to the substation machinery and apparatus, it is advisable that at times of heavy load this be operated well loaded rather than underloaded, thereby reducing the load at the main station as much as possible.

Another matter which has lately been claiming recognition is the regular and systematic keeping of temperature records of all electrical machinery, particularly that which is heavily loaded. One way of caring for this is to install maximum thermometers in all large machines and pieces of apparatus liable to overload, and to take from these regular weekly readings. These readings are tabulated in proper form and come to the headquarters of the operating department weekly with the inspection records. Apparatus which has been seriously overloaded and possibly not reported is then readily noted. It has been found that machines such as turbines, which have to be periodically cleaned by removing the revolving field in order to provide access to the air ducts of the armature iron which are apt to become choked up with dust and grease, are more safely operated if this record is kept, as the gradual rise in temperature due to such stoppages in the air ducts becomes evident week after week by increased values of the readings of the maximum thermometers. This dangerous condition otherwise might pass unnoticed. The method was first brought to my attention by the operating officials of one of the large New York systems.

In the matter of obtaining the lowest possible station cost consistent with reliability, I desire to call attention to a small matter which, however, may be the possible means of effecting a saving which is not always properly taken into account. Detailed costs are generally worked out in fractions of a cent per kw-hr. For certain reasons it is occasionally a good plan to work out all items of cost that pertain to the transportation, unloading, conveying, handling and firing of coal, including labor in the fire room, and ash disposal, also the maintenance of all apparatus involved in the above, including boilers, stokers, etc., as so many cents per ton of coal burned. In this way figures, each of which is directly proportional to the coal burned, will be given more meaning to the foreman and others, than if they are expressed in small fractions of a cent per kw-hr.

For instance, it is an easier matter to make a saving on repairs to boilers or in coal handling, or any other similar items, if we can tell the head of a boiler department that his cost is 15 cents per ton of coal, than if you tell him it is 0.025 cents per kw-hr. A man will work harder to bring this 15 cents down to 12 cents than he will to reduce a very small fraction by a microscopical amount. We will thus have cost per ton at the mine, transportation, lighterage, unloading, conveying, bunker expenses, labor on the fire room floor, repairs to boilers, furnaces, and to the ash conveying machinery, and also cost of ash removal, all expressed in cents per ton of coal consumed.

And right here it might be stated that one of the best means for obtaining economical station operation is to encourage every member of the working force to take care of his particular work in the most careful and economical manner by giving him a desire to do better work and by actually giving him enough information to see that his own work is important and is being kept account of, letting him see that any change in the efficiency of his department, small or large, becomes a matter of permanent record. He thus feels that he is a factor in production and is anxious to do his best. The above method commends itself, also, in that it has absolutely nothing to do with the selling cost and the unit of energy, and is therefore a safe figure to use.

Power factor is a matter which must be carefully watched by lighting companies supplying alternating current load. There seems a tendency in spite of careful engineering, for the power factors to grow lower. It then becomes necessary at certain stages to install synchronous apparatus in sufficient amount to counteract the evil. This synchronous apparatus should be installed at the substation where the power factor is particularly low. This is frequently made possible by the installation of synchronous motors driving arc light generators, which are naturally shut down during the time of day load when the power factor is low, and thus become an extremely convenient means of increasing the power factor. Trouble with low power factors exists in a more troublesome degree in summer than in winter. This makes the generating machinery operate at high temperatures. It therefore becomes very convenient to make use of the reserve turbine unit operated as a motor with over-excited field to reduce the current and temperature of the running machines.

Other corrections for poor power factor, outside of synchronous motors, are in the line of insuring proper voltage to motors and loading them up to the limit of safety. Low power factors are also possible by wrong connections, and in regard to the synchronous apparatus itself, it is very necessary that the substation operators be trained to run with a high power factor or leading current when required, as an under-excited synchronous motor is worse than none at all. When we consider that any load contracted for of a power factor of 50 per cent practically means a doubling of the capitalization per kilowatt involved the importance of good commercial engineering is very manifest.

The transmission system of our large companies is, in great part, underground, and it is necessary that it be as carefully installed and protected as possible. Short-circuits and high-potential surges may be encountered at any time and unexpectedly, and must be cared for. The use of choke coils in the main leads of large turbines is being urged in large 25-cycle installations on account of the necessity for protecting the switching apparatus. The short-circuits that can be obtained from present installations of turbine units in certain plants are enormous, and it is unsafe to rely upon any oil switch yet manufactured to open it. In such a case there seems to be very little choice; choke coils must be installed. On 60-cycle systems, however, the necessity for this protection is not quite so urgent, although it is quite possible that our large stations of this frequency may yet have to be thus equipped.

"The momentary short circuit current of an alternator bears to the permanent short circuit current the ratio

$$\frac{\text{armature self-inductance} + \text{armature reaction}}{\text{armature self-inductance}}$$

"In machines of high self-inductance and low armature reaction this increase of the momentary short circuit current . . . is moderate, but may reach enormous values in machines of low self-inductance and high armature reaction, as large low-frequency turbo-alternators." This is an inherent feature of the turbo-generator. "The momentary short-circuit current is from 40 to 50 times full-load current, which is a fact that in large turbine plants must be carefully considered in connection with the other parts of the system and most especially in connection with switches and circuit breakers."*

In several systems, the neutral of one or more machines is grounded either through a resistance or solid, thus allowing any grounded feeder to cut itself out of commission generally under overload rather than short circuit conditions which relieves the situation somewhat with regard to oil switches. Certain indicating devices have been worked out which show any unbalanced static condition in a cable system, locating the grounded feeder before a short circuit results, and giving the operator warning to immediately cut the feeder out of commission. For an excellent description of such a device see article in the TRANSACTIONS of the A. I. E. E., October 11, 1907, Volume XXVI, p. 1619, by Mr. Torchio.

The installation provided in the case of substations for the direct current districts will generally include a storage battery reserve sufficient to carry them temporarily over any chance loss of current for a sufficient length of time to enable the operators to get the revolving machinery into commission again. Alternating-current substations are generally provided with air-blast transformers, although if the voltage is high, of course, oil-cooled transformers will be used. These transformers may have dial heads for adjustment of primary voltage if desired. Automatic regulators in which the relation between the position of the primary and secondary coils is changed automatically by means of a motor, controlled by a relay operated by a compensating voltmeter attachment calibrated for the special line drop in question, are being installed in large numbers and are giving excellent satisfaction on these 2200-volt circuits of the alternating-current distribution system.

This induction regulator is essentially a transformer, in that, neglecting the slight loss in the regulator itself, the product of volts and amperes on the primary side is equal to the product of volts and amperes on the secondary. The primary is wound for full line voltage and acts as the exciting coil, being connected directly across the line. The secondary or stationary element carries full load current and is directly in series with the line. The flux set up by the current in the primary affects the secondary or series winding according to its direction and intensity. The neutral point is where the two coils are at right angles.

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* Steinmetz "Transient Phenomena", p. 201, and Proceedings of the N. E. L. A., 1909, p. 154.

Rotating the primary in either direction from the neutral impresses a voltage on the series winding which increases or decreases the line voltage as is desired. In order that the wave form may be preserved, both primary and secondary coils are designed with as many slots as possible, and, in order that the secondary may not, by the field set up by its own current, act as a choke coil, and thus lower the power factor of the regulator, the primary winding of these regulators is provided with a short circuited winding at right angles to the main winding. With the regulator on the neutral position this causes the primary to act as a short circuited secondary of a transformer so that the choking effect of the secondary flux is eliminated. The power factor of the regulator is fairly high, and as the capacity of the regulator itself is rarely more than 10 per cent of the circuit capacity its effect in reducing the power factor of a lighting load is but a fraction of one per cent.

Voltage schedules on the 2,200-volt circuits are made out by the department of distribution and forwarded to operating headquarters, giving the pressure to be maintained at the substation voltmeter with each change of load in amperes. These once in effect are not changed or departed from in any way until superseded by new schedules properly approved and forwarded to the substation. Each circuit panel carries this voltage schedule card in a card holder on the panel itself, so that it is always available for checking.

A slight use of the vector diagram will readily show that for circuits of variable power factor—for instance when the day load consists of motors giving a power factor of 70 per cent, and the night load which is mostly a lighting load, with a power factor of 95 per cent,—no one voltage schedule based on amperes alone will properly care for the voltage at the load center. In this case the voltmeter and relay control for the induction regulator must be compensated for the line characteristics. With substation voltmeters corrected by compensation for line constants, all the voltmeters in the stations will read practically alike, or the voltage at the consumers' premises, and the mental calculation of the operator in following schedules, which in a station of many circuits becomes practically impossible, is made unnecessary. The line e.m.f., of course, varies with each circuit.

The keeping of records is an important part of an operating system. The exact records to be kept and the details to be followed will necessarily vary with the size and type of the system involved. As the system grows, detail becomes more and more necessary and the blending of the reports of the different branches into one complete whole, which will give us exactly what we may require at some future time, and yet which will avoid repetition and unnecessary labor, becomes the subject of considerable thought. First in importance, perhaps, among the operating records comes the station log book. This is a daily entry of all the main facts concerning load, engines on line, boilers in service, being repaired, cleaned, etc., pumps and their operation and, in fact, covers the operation of the plant and system. Thus, the log book for a station of 5,000 kw. would be entirely inadequate in the case of a plant of 25,000 kw., and the operating records of a 100,000-kw. plant naturally would involve greater detail than those of a 25,000-kw. plant. The object in keeping the station log book is two-fold; for assistance in laying out plans for daily operation and future growth, and secondly, for keeping on record certain important facts which may be called for at any time. In small stations these records are kept by one man as a part only of his many and varied duties. As the system grows larger this work increases so rapidly that a man will have very little to do outside of what pertains directly to his log-keeping. About this time it also becomes necessary for the data to be given to the log-keeper, as he has no time to look it up. This will be taken care of probably by the regular reports of minor departments. With a still larger system, two separate log books will be kept, one for the mechanical and one for the electrical department. The entries in these books will then be made directly by the operating men themselves and will become records at first hand. Engineers and electrical foremen operating on successive shifts will sign the log of the preceding shift as well as that of their own to put themselves on record that they have made themselves familiar with the operating conditions under the previous shift. Reports in abstract will now be taken from two log books instead of one.

Of the office records of a generating system, next in importance to the log book comes the card index system covering in detail every piece of apparatus in the system with the date of installation, first cost, order number, and a complete description, including a name-plate, serial number, etc. so that information is at hand in case replacement or spare parts are desired. This not only applies to every engine, generator, exciter, battery, etc., but to every piece of machinery and apparatus in operation which is liable to have trouble and need repairs. It thus includes a record of all series and potential transformers, air blast transformers of alternating and direct current substations, rotary converters, motor generator sets, etc. Each large piece of apparatus bears a specific number which is entered on requisition, whenever necessary, in order that all expenses involved in connection with any piece of apparatus may be entered on record in connection with the card itself, so that at any time a system with proper records should be able to give the maintenance charge against any piece of apparatus desired, whether this is asked for yearly or after a period of years.

In order to weld the whole operating force, electrical and mechanical, main station and substations into one compact whole so that concerted action may be possible, instruction sheets specifically intended for one particular branch are distributed throughout the system. These are kept in binders provided for the purpose. Blue prints covering bus bar wiring of every station are sent to all stations for the same reason, as are also detailed prints giving the switchboard panels with every instrument, switch, etc., numbered, and covered by card in card index system as stated before. Each operator is then in a position to advise with regard to the disablement of any particular part of his apparatus by merely referring to a drawing and panel number. In this way it is frequently possible to save considerable time in making repairs and in getting reserve apparatus into commission. It also assists materially in instructing the operating force, broadening their knowledge and making them think for themselves.

In a large and complicated system it will generally happen that a miniature of the system covering every machine, bus bar, switch, cable, piece of machinery in both main and substation will be found necessary for the assistance of the main station operator. Apparatus in service and position of switches will be indicated by appropriate markings. This exemplifies the necessity for a central station operator on the main board or in close touch therewith.

Complete detailed drawings and card index should also be kept of the various piping systems, valves, etc., of the mechanical department of the generating station. All important valves of the plant should be numbered and each should also bear a tag with its number, and description of the valve. Reference to valves will always be made by numbers. Instruction sheets are also issued in this connection with special cuts covering, for instance, detail of step bearings, middle bearings, upper bearings, of turbines, etc., showing oil grooves and general construction. In a system involving a great complexity of piping, as is necessary in plants of a large size, too much care cannot be taken that the men are carefully drilled with regard to the location and exact function of every pipe and valve, giving them a better knowledge of the complete system rather than that of only the particular part of the same in their immediate vicinity. This system of blue prints and records gives all men a chance to offer suggestions, without which feature the best of operating systems is working under serious disadvantage. Piping systems in large stations are generally painted in special colors to better designate their specific function.

With growth comes a necessary division of responsibility which necessitates an organization that will work smoothly yet flexibly in order that proper care and attention may always be given to every detail. Slight defects are occasionally found in machinery or apparatus of the method of caring for the same. These may be of more or less importance, possibly not at all dangerous in themselves, but collectively they have an influence tending to lower the standard of the station equipment. To give good and reliable service, all machinery, switches, etc., must be kept in first class condition at all times. Therefore, to guard against omissions of inspection, or any possible oversight or infringement of regular operating rules, a careful system of inspection and checking is necessary. Every piece of apparatus and every special inspection, or regular overhauling of a piece of machinery, every emergency drill and test, is cared for under specific inspection number. These are grouped according to departments and according to periods of inspection. The main inspection sheet, carrying the list of inspections necessary, is grouped into as many columns as there are week ends in the month. All inspections made, therefore, during the above week are noted by special marks opposite their names, and the initials of the foreman, engineer, or assistant making the specific inspections are required opposite each item.

At the end of every week the complete list of inspections not made or machines or apparatus not in perfect condition, rules which have not been complied with, or any departure from regularity in test or otherwise, is abstracted from the weekly detailed inspection sheet and sent to the office of the operating head by the main department chiefs. The signing of this inspection card in itself constitutes an order to have such discrepancies corrected before the next succeeding week. No item is expected to appear on the inspection card for two consecutive weeks. The system of inspection is made absolute, and it therefore rests with the operating head whether he will accept conditions as they are, or insist upon them being corrected. The natural result of this system has been a higher ideal of excellence in both equipment and station conditions, and an increased spirit of confidence, which is essential for the best results.

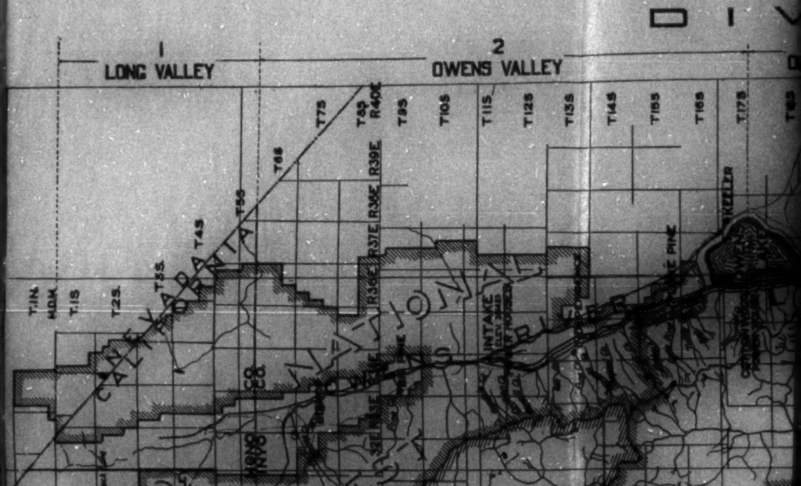
Another important point which assists in maintaining a high standard of reliability is the selecting, training, drilling and redrilling of the working force. It is not enough that the directing head be well assured that every man in his system knows his duty in times of trouble as well as when things are running smoothly, although this in itself is no slight undertaking, but he must be absolutely assured that each man will act as his best knowledge dictates under all conditions. A man can only get acquainted with accidents by experience. A majority of accidents due to the breaking down of apparatus never occurs after the first time. It will not be questioned, therefore, that the value of the operating man to the company increases directly with his length of service. There are, unfortunately, occasional accidents due to mistakes of the men themselves. As a rule these are not due to ignorance. A great majority of them are made by men who have been trained and who know better. There are times when a man's brain and hand do not act together. The elimination of this class of mistakes is a necessary step in the direction of good service. Mistakes can be made in construction and in design which may never appear excepting to a limited few, but an error in operation appears in ever widening circles, reaching possibly the remotest consumer on the company's lines.

As a fundamental requirement therefore, we will grant that our active operating men must be given reasonable hours, good pay, reasonable prospect of advancement, as the occasion may offer, and be relieved as far as possible from worry and annoyance of any kind. Without good organization throughout the whole generating system, this is impossible.

There are thrown every year in a certain substation system, 197,000 switches, a mistake in any one of which might perhaps cause local trouble. The quality of service given by large companies, however, shows that the errors here are comparatively few. They do, however, occur occasionally. In the main generating station of the same system there are thrown yearly some 52,000 switches. A mistake here is more far reaching in its effects than a corresponding mistake in any substation, as it may possibly involve the whole system. By exercising great care the number of mistakes of this latter kind are very few, possibly none at all being made which involve anything more than local trouble. To eliminate these few remaining errors, however, and to provide against unforeseen contingencies, a rule that every operation involving main station switching excepting in minor cases, must be checked by another operator or foreman whenever it is physically possible has given considerable ground for satisfaction.

Finally comes the choosing of the working force and the selection of the foreman, engineers and assistants. This, at first, might seem the easiest part of the whole. There are, however, very many points to be considered even in the selection of men in minor positions. It must always be borne in mind that the helper may one day be an engineer or a foreman or even more. In the choice of men for the various positions of authority, those must always be selected who have, together with other qualifications, the ability to handle men and the capacity for growth. At times the choice of a man to fill the larger positions is self-evident. In order, however, to avoid even the semblance of partiality or favoritism, it has occasionally been found a good plan to give each applicant an examination based on such attributes as a man in the coveted position should have. These will involve such points as honesty, ability to handle men, ability to achieve results, cool headedness, technical knowledge, mechanical ability and others. A sheet is prepared for each name, bearing in column form the various attributes, given, with their relative values, by the head of the department. An examining board, composed of assistants of experience, each of whom has a sheet for every applicant, places such values on each man's sheet as his own experience and knowledge of the man in question would seem to entitle him. Each name is completely marked before the second name is considered; so there can be no recollection, even unintentional, of what numbers the preceding man has obtained. The figures are then carefully added up in the office, and corresponding grades attached. It is a peculiar fact that it rarely happens there exists any real difference in opinion as to who is the best man for the position. The value of this method, of course, lies in the fact that it is absolutely impartial. Every man on the examining board must be trained in matters pertaining to the operation of stations and central station systems in order to make it effective. The use of veto power will rarely be found necessary.

Finally, equal in importance with preserverance, wholehearted service and painstaking insistance on high standards on the part of every man in the department, is proper company organization and recognition of faithful and efficient accomplishment.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CALIFORNIA
NEVADA
MONO CO.
INYO CO.
LONG VALLEY RESERVOIR
INTAKE
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LONE PINE
KEELER
OWENS LAKE
MONO LAKE
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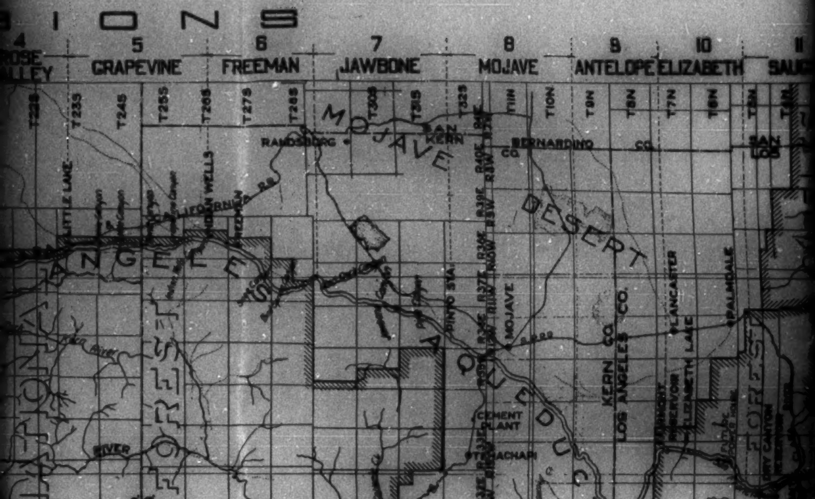
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RANDSBURG
MOJAVE
SAN BERNARDINO CO.
KERN CO.
SAN LOS
DESERT
LITTLE LAKE
INDIAN WELLS
FREEMAN
NEVADA CALIFORNIA R.R.
SEQUOIA NATIONAL FOREST
Kern River
RIVER
TULARE CO.
KERN CO.
TULE RIVER INDIAN RESERVE
CINCO STA.
MOJAVE
CEMENT PLANT
TEHACHAPI
AQUEDUCT
KERN CO.
LOS ANGELES CO.
LANCASTER
PALMDALE
ELIZABETH LAKE
FAIRMONT RESERVOIR
DRY CANYON
KERN
BAKERSFIELD
KERN
SOUTHERN PACIFIC
SANTA FE R.R.
TAFT
Buena Vista Lake
KERN CO.
VENTURA CO.
SANTA BARBARA NATIONAL FOREST
VENTURA CO.
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ELECTRIC POWER IN THE CONSTRUCTION OF THE LOS ANGELES AQUEDUCT

BY E. F. SCATTERGOOD

The Los Angeles aqueduct extends from the intake in Owens valley, about 12 miles north of the town of Independence, to the storage reservoirs at the head of the San Fernando valley, about 24 miles distant from the city of Los Angeles, from which point the city water department will take care of the distribution of the water. The length of the aqueduct proper is, therefore, 240 miles.

From the southern end north to the north portal of the Elizabeth lake tunnel, a distance of 35 miles, the work is heavy, being to a considerable extent composed of tunnels, including the Elizabeth lake tunnel, some 27,000 ft. in length, through granite rock. Preliminary estimates showed that in such sections the considerable amount of power required could be furnished much more cheaply, from a central generating plant and distributed by high tension transmission, than by small power generating units, either by steam or distillate engines at various points as required. This section is supplied with power purchased from the Southern California Edison Company, and delivered at one of its substations about four miles west of the aqueduct line and near the center of this section. From the Elizabeth lake tunnel to a point 55 miles further north, the aqueduct follows along the desert in the open, and estimates indicated that the conduit excavation, and concrete work of lining and cover, could be done more cheaply with the use of steam shovels and gas engines than by the erection of a temporary electrical generating and distributing system. From the Pinto hills north to the intake, a distance of 150 miles, there are alternate sections of the heavy tunnel work and of the lighter conduit work. In the Owens valley there are numerous creeks flowing down the eastern slope of the Sierra Nevada mountains offering excellent opportunities for power in sufficient quantities for construction work on the aqueduct; and estimates showed clearly that power could be developed at these creeks and transmitted along this 150 miles, and delivered to all points requiring power, in large or small amounts, at a very much lower cost than that for which it could be furnished in any other way.

It should be stated for the benefit of those who are not so familiar with the city's project, and who may read this paper, that the power referred to here is for construction purposes only, and should not be confused in any way with the large amount of electric power which may be developed along the line of the aqueduct when it is in operation, and which will total a peak load capacity of 120,000 h.p. delivered at step-down voltage in the city.

Power System

For the purpose of supplying power along the section of the aqueduct from the intake to the Pinto hills, hydroelectric plants were installed on Division and Cottonwood creeks. The Division creek plant is about three miles south from the aqueduct intake, and has a rated capacity of 600 kw. The works at the point of diversion at the creek cost $1,214. The penstock starting from this point, and extending down the slope 10,500 ft., consists of 6,291 ft. of 18-in. riveted pipe and 4,209 ft. of 15-in. lap-welded pipe, and cost, in place, $28,102. The effective head obtained is approximately 1,200 ft. The power house equipment consists of one tangential wheel direct connected to a 2200-volt, three-phase, 600-rev. per min. generator and a bank of transformers, stepping the voltage up to 33,000, each of which has a continuous overload capacity of 25 per cent above the 600-kw. rating. The power house is built of concrete in a substantial manner. This is also true of the second one to be described, as these plants are intended to become a part of the permanent aqueduct power system. The cost of the power house and equipment, including three cottages, etc., is $21,100, making a total cost of approximately $84.50 per kw., or $63 per h.p. rated capacity at the switchboard.

The Cottonwood power house is approximately 40 miles south from the Division creek plant. Its equipment consists of two tangential wheels, operated under 1,200 ft. effective head, each direct connected to a 750-kw. three-phase, 2200-volt, 600-rev. per min., generator, each of which in turn is connected to the 33,000-volt line through a separate bank of transformers. The works at the diversion point cost $3,964. The canyon for a distance of 3,750 ft. is so precipitous as to make a conduit or tunnel impracticable within reasonable cost, therefore, a 24-in., No. 12 gauge, riveted pipe was buried along the side of the canyon, at a cost of $9,352. From this point to the forebay, a distance of 7,042 ft., a covered concrete conduit, 30 in. by 20 in. inside section, was constructed on the mountain side at a cost of $11,228. The penstock, with 523 ft. of 24-in. pipe and 4,009 ft. of 22-in. pipe, or a total of 4,532 ft., cost $29,820. The power house and camp complete cost $49,638, making a total of $69.40 per kw., or $51.75 per h.p. of rated capacity at the switchboard, the plant having 25 per cent overload capacity.

Cottonwood power house—two 750-kw. generators—power all utilized for construction work

The transmission line is 151 miles long, and is made up of three No. 4 bare copper wires; two-part seven-inch porcelain insulators with iron thimbles, pins and bases; one wire on a 15-in. crossarm at the top of a 30-ft. pole, and two on a 6-ft. crossarm below, and poles spaced 180 ft. apart. The average cost of this line is $862.50 per mile. About one-fifth of this line is through rough mountainous country, and the wagon haul for the entire line an average of 12 to 15 miles. This line has since been extended from its southern end to the aqueduct cement plant, a distance of 17 miles, with No. 2 copper, at a cost of $1,050 per mile. The object of this extension is to deliver surplus power to the cement plant, with the advantage of supplementing the steam plant, thus saving fuel oil and making the entire system more flexible and reliable by running in parallel with two 750-kw. steam turbines at that point. Had the cement plant been contemplated originally, more copper might have been used along the whole line, and more generating capacity installed to advantage. As an interesting illustration of the value of synchronous condensers in connection with transmission of electric power, it may be stated that while delivering a distributed load of 1000 kw. between the intake and the Pinto hills, 400 to 420 kw. could be delivered at the cement plant, 125 miles from Cottonwood at 30,000 volts with 35,000 volts at Cottonwood when not in parallel with the steam turbines; and that 800 kw. can be delivered at the cement plant when running in parallel, by strengthening the field of the turbo-generators, with the same voltage drop and the same distributed load along the line.

Floating transformer station used in connection with suction dredge; Owens Valley

There are about 74 step-down transformers connected to this line in banks of two or three; most of these transformers are of

40 kw. capacity, the remainder are either 20-kw. or 80-kw. The greater number are of the out-door type, which have given excellent satisfaction, and are very much liked by the men in charge of work, because of the decreased expense and time of setting them up. Most of them have been shipped from the factory with the oil in them, as they are in boiler iron cases, made suitable for moving with the oil in place, thus avoiding the necessity for drying out of transformers at isolated places. The protection of this high-tension line against lightning and surge voltages is a combination of low-equivalent arresters at the Cottonwood power house and three sets of horn-gap arresters at other important places. The transformer stations are protected by air-insulated choke coils and fused horn-gap switches. The comparatively small insulators for the voltage used, while they have given no trouble whatever, do undoubtedly serve to give additional protection to apparatus along the line by affording relief from any excessive potential. No apparatus has been lost from lightning or surges during the eighteen months of its operation.

By including interest, placing a proper depreciation on the permanent power plant, and assuming a low value of return from the copper on the temporary line, and on the transformers constituting the substations, (the system to be in use but four years), it was estimated that the cost per kilowatt hour delivered at a step-down voltage, in large and small quantities as desired, would be approximately 1.15 cents. The indications are that this estimate will prove to have been conservative.

Uses of Electric Power

Stating as briefly as possible the uses to which this power is put; there are in Owens valley about 20 miles of the aqueduct which can conveniently be built with dredges. Four electric shovels are in use for conduit excavation in the open country. One mill for regrinding tufa with the cement is located at Haiwee, 22 miles south of Cottonwood. Electric power is used at Haiwee, also for sluicing and other work connected with the building of the earthen dam. There are approximately 18 miles of rock tunnels and three miles of earth tunnels provided for by this power system. The typical tunnel equipment consists of one air compressor, driven by a 100-h.p., 440-volt, three-phase induction motor; one 80-kw. motor-generator set, providing 250-volt direct current for electric locomotives; lighting and other work inside the tunnels; other power for blowers, machine shop, hoists, pumping, etc., as the case may be, and for lighting camp. In case electric locomotives are not used, as in shorter tunnels, alternating current at 110 volts is used for lighting in the tunnels also.

Dredges. There are two suction dredges in operation in Owens valley, each equipped with a 12-inch centrifugal pump, driven by a 100-h.p., 440-volt induction motor; one 40-h.p. motor to run the cutter, one 40-h.p. motor to run the jetting pump for breaking down the bank over the cutter, and one 20-h.p. motor for operating various hoists. There is also one dipper dredge of one and one-half yards capacity, of the friction type, driven by one 100-h.p. induction motor. The step-down transformers in each case are mounted on a float, with the rack overhead supporting the choke coils and switch on which the taps from the transmission line land. The line being close by requires but one short span, and a crossarm is placed on the round cedar pole by clamping it with two bolts and a short piece on the back, as shown in the illustration, then pushing up at a safe distance from the lower arm. Connection is made with the line through long spiral springs of tempered brass and a brass clip at the end. These are put in place by means of a long pole from an insulating stand, or by climbing a short distance up the power poles, with the line switches at the transformers open, and the transmission line hot, which necessity requires, and which cannot result in

Dipper dredge in Owens Valley

personal harm when done by an experienced lineman, as is the case. The connection from the transformer float to the dredge is made by means of a three-conductor submarine armored cable. The cable is stored on a reel on a second float attached behind the dredge, with flexible connections to the dredge, so that the cable is automatically paid out, and when all out the flexible connections are detached and the cable wound up, then the reel float and the transformer float are towed up to the dredge together. This method has proved very satisfactory in avoiding abuse to the cable and in saving time and expense in moving.

Method of connecting portable substation to 33,000-volt transmission line

Electric Shovels. Electric shovels with three-quarter yard buckets, and 25-ft. booms, used for conduit excavation, are of the friction type, driven by one 75-h.p., 2200-volt induction motor. The step-down transformers are mounted permanently on sleds or trucks, with the racks supporting the choke coils and switches permanently fixed overhead, and with two 10-kw., 2200- to 440-volt transformers attached, supplying power for concrete mixers operated in connection with each shovel. The cable used is three conductor No. 10 with rubber insulation, rounded out with jute, taped with weather-proof braid and half round steel armor over all. This connects between the transformers and the shovel and between the temporary 440-volt line on the power poles (about 1000 ft. back from the transformers) and the mixers, and is giving excellent satisfaction. The considerable advantage experienced with the use of out-door type transformers in connection with dredges and shovels is very evident.

Electric Locomotives. Twelve three-ton electric locomotives rated at 1200 lb. draw-bar pull at six miles per hr. are in use in this section of the aqueduct. At each end of the Elizabeth tunnel, which is not supplied from this power system, there is one locomotive of this size and one six-ton locomotive. In that tunnel, which is approximately 90 sq. ft. in section when lined, the larger locomotive is preferred, making it possible to pull out 14 to 16 cars of muck at one time. The three-ton locomotives are of good size for the tunnels in the section under consideration, which are approximately 70 sq. ft. in finished section, and range from 2000 to 10,000 ft. in length where locomotives are used. The use of electric locomotives in these tunnels results in a reduction in cost of excavation and placing the concrete lining, which is a considerable percentage of their total cost. The actual cost of removing muck and delivering concrete is considerably less than it would be if done in other ways, especially by mules; but the greater reduction in cost is due to the practical condition of being able to get the muck away for the convenience and economic working of the miners in excavation, and allowing the placing of rock crushers and concrete mixers at a conveneint point outside of the tunnel for concrete work. Concreting is being done successfully and with perfect satisfaction to the engineers at a distance of 10,000 feet in one instance. This use of these machines makes it possible not only to reduce

Electric shovel on open conduit; Mojave Valley the cost where speed is not a consideration, but to very materially increase the speed, if desired.

Small Isolated Power. Experience with distillate engines in connection with concrete mixers and other small power has led the men in the field to plead for electric power; for example, several steam shovels are in use in this section for conduit excavation, and it was thought at first that the expense of stepping down the voltage, moving transformers, etc., for supplying two or three motors of 7½ to 10 h.p. each would not be justifiable but the division engineers now insist that the cost of maintaining and operating distillate engines under the conditions experienced along such work is in itself greater than the cost of supplying the electric power, including the charge made against

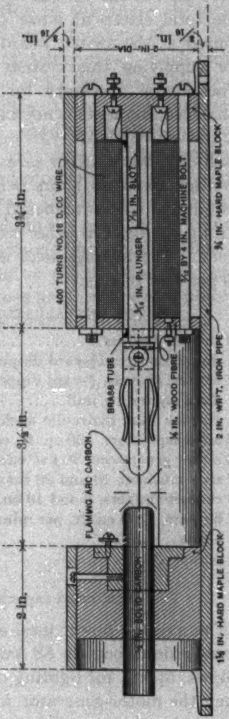
33,000-volt portable substation—outdoor type transformers them for the energy, as well as the equipment, beyond the transformers; and they further state that the interruptions which they have experienced in concrete work with distillate engines behind a single steam shovel, as compared with what they have experienced in concrete work with electric power behind an electric shovel, has cost them anywhere from $20 to $40 a day after the engines had been in use a few months and began to develop troubles under those conditions of operation; in other words, the saving is due to the consideration of reliability aside from actual cost of supplying power to the mixers. The cost for tunnel work is considerably reduced and the speed increased by electric lighting. The illustration herewith shows a type of home made cluster, which is giving excellent results at the headings.

Electric mine locomotive; Elizabeth Lake tunnel

Protection Against Gases

One of the long tunnels in another section runs through an oil district, and at times has developed considerable explosive gases. In order to protect the men against this danger, electric sparking devices have been installed, designed as shown in the illustration. They may be operated either by alternating or direct current. They are operated by direct current in this case by means of a switch outside of the tunnel, and as may be seen, are absolutely positive in their action and cannot fail if properly trimmed when the miners leave the tunnel. They have exploded gases several times, and in the form shown are usually found intact after the explosion; several of them being in use gives opportunity for further trials before entering the tunnel.

Lamp cluster used in tunnels and designed to reduce lamp breakage from blasting, etc., to a minimum.


3/16 in.
2 IN. DIA.
3/16 in.
3¾ in.
400 TURNS NO. 18 D. CC WIRE
⅛ IN. SLOT
5/16 IN. PLUNGER
5/16 BY 4 IN. MACHINE BOLT
¾ IN. HARD MAPLE BLOCK
3⅛ in.
BRASS TUBE
FLAMING ARC CARBON
¼ IN. WOOD FIBRE
2 IN. WR'T. IRON PIPE
2 in.
¾ IN. SOLID CARBON
1½ IN. HARD MAPLE BLOCK

Sparking device for exploding gas in tunnel

AMOUNT OF POWER REQUIRED

A good idea of the amount of power necessary to operate the equipment may be obtained by studying the following tabulation, which gives the total rated motor capacity, approximately 3470 h.p., of the various equipment attached to this system, and the total electrical horse power, approximately 2000 h.p., required at the switch board of the two power plants combined for supplying this system independent of the cement plant. The energy necessary for lighting machine shops and other small requirements is not tabulated, but is included in the power at the switchboard. In many instances power is used 24 hours each day, but in other cases during 16 or 8 hours per day; on an average about 16 hours per day. The amount stated as being required at the switchboard is taken from the heavy load periods during the day; in other words, the average peak load for that work. The average load during the 24 hours would be about 60 per cent of this.

MOTOR INSTALLATION INTAKE TO PINTO HILLS

2 suction dredges	400	h.p.
1 dipper dredge, 1½-yard dipper	100	"
4 electric shovels, ¾-yard dippers	300	"
Tufa regrinding mill	200	"
Haiwee dam, hydraulic work	100	"
8 air compressors, 500 cu. ft. each	800	"
8 motor generators, 80 kw. each	1000	"
7 rock crushers, 10 and 20 tons per hour each	140	"
28 concrete mixers, 6 and 10 cu. ft. per batch	280	"
7 blowers, 1350 cu. ft. per minute each	70	"
3 hoists	60	"
2 pumps	20	"
Total rated capacity of motors	3470	"

The average power used at each end of the Elizabeth tunnel, already described, is 88 kw. during the 24 hours, divided, as follows: 5½ kw. for lighting outside the tunnel; 35½ kw. for operating the motor-generator which supplies power for ventilation, electric locomotives, lighting the tunnel and a small amount of pumping from the tunnel; and 47 kw. for compressed air for drilling, machine shop, camp water supply, etc. The average peak is about double the average load.

TELEPHONE SYSTEM

The telephone system is considered not only one of the most profitable adjuncts to the aqueduct construction, but one which is essential to its economic construction at reasonable speed. It consists of approximately 260 miles of main line from the Los Angeles offices to the intake, built of two No. 10 copper wires strung on redwood poles, at a cost of $188 per mile. This line is divided in three sections by two exchanges, which more than doubles its efficiency. In addition to this there are local telephone systems in each of the various divisions along the work; some of these have as high as 26 telephones. Each local system may be temporarily connected with the main line by a switch in the division engineer's office, there being but one main line telephone on each division. As the telephone system is to be used by all classes of men, very few of them familiar with electrical work, it was though undesirable, if not wholly impossible, to operate it successfully with the line on the power poles. Estimates showed that by making the poles on the transmission line five feet shorter, the telephone line could be placed on separate redwood poles at an equal or slightly less cost, and this has been done. The telephone lines are in every case placed underground at crossings with high-tension electric lines.

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DIVERSITY FACTOR

BY H. B. GEAR

In the distribution of electricity for lighting and power purposes over a large city, the maximum demand of the day upon the distributing system varies from day to day during the week, and from month to month during the year. The varying length of the day due to changing seasons, the habits of the population served, and the character of the district, whether residence, mercantile or manufacturing, combine to produce this situation.

In residence districts, for instance, the use of light is such that the maximum demand comes at about 7:00 p.m. in winter and at 8:30 p.m. in mid-summer, as shown in the load curves in Fig. 1. In outlying business districts in the large cities and in the central business districts of the smaller cities, the maximum demand comes from 5:30 to 6:00 p.m. in winter, or at 8:30 p.m. in summer. It is usually heavier Saturday than other nights of the week. In the central business districts of cities like Chicago the maximum demand comes from 5:00 to 5:30 p.m. in winter, and at various other hours in summer. Here the Saturday load is less than that of other days because of the early closing of offices and shops that day. This is also true of manufacturing districts where the load is chiefly power. In a purely manufacturing district the maximum load occurs at about 10:00 a.m., the afternoon load being from 15 to 20 per cent less than the maximum of the morning. The load curve in Fig. 2 is that of a power circuit which carries some lighting and so has a 5:00 p.m. maximum.

In the larger cities the conditions vary in all of these classes of service more or less with the character of the population.

The habits of the people in the foreign populated wards are different from those bordering on the boulevards, and the requirements of dwellers in apartments are different from those living in houses. In the outlying districts of Chicago, stores are closed Wednesday and Friday evenings, while in downtown districts very few stores are open evenings at all and the use of electricity is limited largely to show window and display lighting. During the summer the loss of demand in residence districts is partially made up by the requirements of the pleasure parks The combined curve for these various classes of service is shown in Fig. 3.

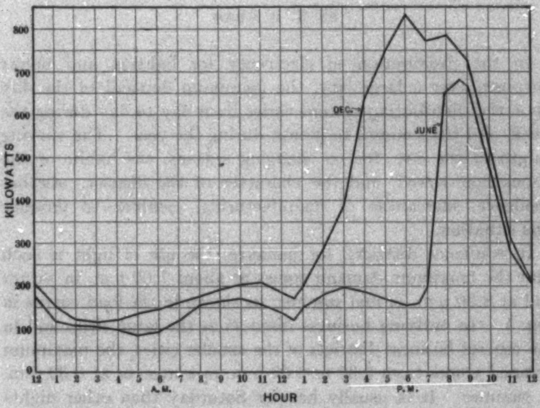

FIG. 1

The combined effect of all these influences is to produce a smaller maximum demand at the generating station than elsewhere in the system. That is, the sum of the maximum demands of the transformers and distributing mains is greater than that of the feeder. The sum of the feeder maxima is greater than that of the substation, and the sum of the substation maxima is greater than that of the generating station.

The ratio of the sum of the maxima of the subdivisions of the distributing system to its actual maximum demand as observed at the point of supply is called the *diversity factor*. Thus, if the sum of the individual maximum loads on the ten feeders of a substation is 1200 kw. and the co-incident maximum of the feeders is 1000 kw., the diversity factor is $\frac{1200}{1000}$ or 1.20.

The study of diversity factors is of great importance from a commercial point of view as well as being an interesting engineering problem. The investment required by the central station company in the various parts of its operating system for each kilowatt of maximum demand, determines the fixed charges which must be considered in determining costs and in making an equitable system of rates.

The existence of a diversity factor between the demands of a large number of consumers permits the central station company to supply their demands with a much smaller investment in generating capacity and at a lower cost of production than would be possible if these consumers were operating individual generating plants. This difference must be sufficient to enable the central station to add the financial burden of a distributing system and yet have a margin upon which to sell its product economically to its consumers. The effect of the diversity factor is therefore a subject of interest to both producer and consumer of electricity.

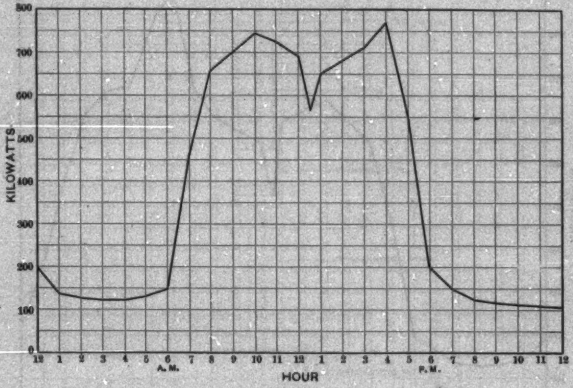

Fig. 2

The larger the system the greater the diversity factor and our study will cover an alternating current system supplied by substations, feeders, mains, transformers, etc., as shown in Fig. 4. An alternating current system has been selected for analysis as it is somewhat easier to observe than a direct current low tension system because of the presence of transformers whose loads may be measured. The loads on the distributing mains of a low tension feeder are not so easily measured, and observations therefore cannot be readily made.

The consumer being the originator of the demand for electricity, the development of the diversity factor logically proceeds in the reverse direction from the flow of energy.

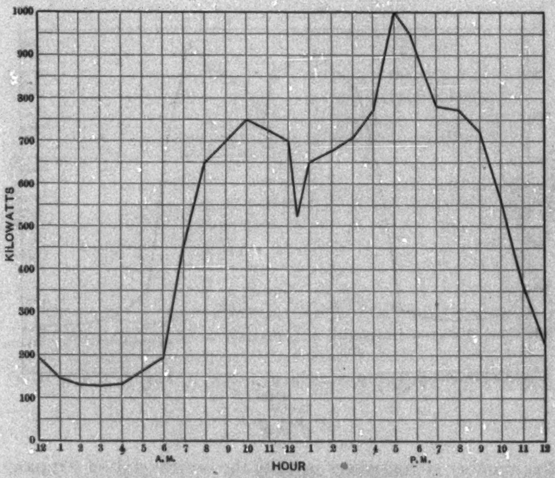

Fig. 3

Observations made in residence districts supplied by overhead lines indicate that the sum of the maximum demands of individual consumers is from two and one-half to three times the co-incident maximum demand on the transformer, the ratio being lower where there are less than ten consumers on a transformer and higher where there are more than thirty.

In commercial districts with numerous small stores supplied by overhead lines, as illustrated in Fig. 5, the co-incident demand is much higher in proportion to the consumer's demands.

The ratio of the sum of consumers maxima to the co-incident demand in this class of lighting is found to be from 1.5 to 1.7, it being lower where there is considerable display lighting, show-windows, etc., and higher where the shops are of such a character that not all the lighting is needed continuously.

In the block of commercial lighting shown in Fig. 5 there are fifty-five customers, twenty-six services and 1200 lights connected. The measured demand on the transformer at 7:00 p.m. Saturday is 34 kw. while the sum of the readings of the demand meters is 55 kw. The diversity factor is therefore $\frac{55}{34} = 1.6$. The sum of the demand meter readings is 55/60 of the connected load.

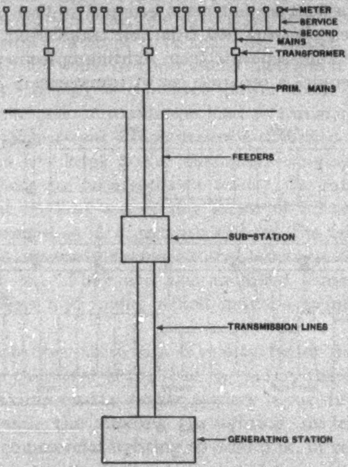
METER
SERVICE
SECOND MAINS
TRANSFORMER
PRIM. MAINS
FEEDERS
SUB-STATION
TRANSMISSION LINES
GENERATING STATION

Fig. 4

In a densely populated residence block in Chicago the connected load is 2100 50-watt lamps or 105 kw. The consumers' maximum demands aggregate about 63 kw. and the co-incident maximum, as measured at the transformer, is 18 kw. There are over 175 consumers connected to the transformer. In this case the diversity factor is $\frac{63}{18} = 3.5$, and the consumers' demands are 63/105 of the connected load.

This probably represents as dense a condition as would be found anywhere in a residence district. It is due in this case to the fact that the block supplied by this transformer consists entirely of three-story apartment buildings, in which about 90 per cent of the tenants are using electric service.

Power consumers are not often grouped so that any considerable number can be supplied from one transformer installation. They must be kept separate from lighting customers and therefore usually require a separate set of transformers for each consumer where the load is 2 h.p. or more. In large installations advantage is taken of the diversity between motors to reduce the transformer capacity installed. This cannot be done with small consumers except in the occasional situations where several power consumers are located within a radius of about 500 feet.

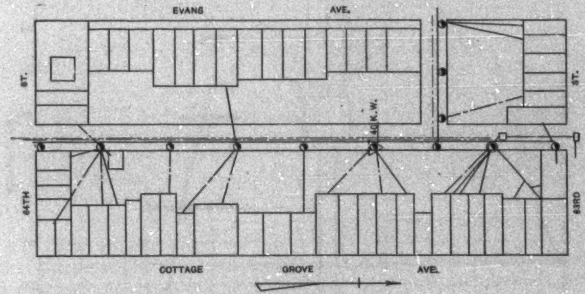

Fig. 5

The diversity factor between meter and transformer on power customers is therefore very small and probably does not average over 1.1 for all power installations.

Advancing toward the substation, the next point at which diversity may be conveniently observed, is at the feeder switchboard. There is a considerable diversity factor between the sums of the transformer maxima and the maximum feeder load.

The factor varies with the character of the territory served and with the density of the load. In scattered residence territory where there are many one, two and three-kw. transformers, and few larger than 15 kw., the ratio of maximum feeder load to total transformer capacity is from 45 to 50 per cent. In territory where transformer units vary from 5 to 30 kw., or larger, the ratio is 55 to 60 per cent. In commercial districts with transformers from 5 to 50 kw., the ratio is from 75 to 85 per cent or higher.

Assuming that each transformer carries its rated load at some time during the year, the diversity factor for a feeder in scattered territory is from 2 to 2.2. In denser territory the factor is 1.6 to 1.8 while in commercial districts it is 1.2 to 1.3.

On circuits carrying a scattered power load in units of 5 to 100 h.p., the ratio of maximum load to transformer capacity is from 45 to 50 per cent which makes a diversity factor of 2 to 2.2. Where a few large power customers ranging from 100 to 500 h.p. or more are on a separate feeder, the ratio is from 75 to 85 per cent, making a diversity factor of 1.2 to 1.3. These ratios shift somewhat in a growing system, the tendency being to reduce the diversity factor as the territory becomes more densely built up. They are also modified somewhat by the losses on feeders and mains which may be as much as 15 to 20 per cent.

In the substation, there is a diversity factor due to the difference in the character of the load carried by the different feeders. The maxima on the power feeders occur during the daylight hours while the maxima on lighting feeders vary from 5:30 p.m. in commercial lighting to 7:00 p.m. in residence lighting.

With three-phase distribution, there is a diversity factor between phases where the lighting is carried single-phase. The net result is that in a substation with ten or more feeders the diversity factor averages about 1.15. In the substation supplying power feeders and general lighting it is likely to be as high as 1.2 while in a residence district with little power load, it is about 1.1.

Having thus analyzed the diversity between the various elements of the distributing system it is of interest to derive the total diversity factor from substation to consumer for various classes of business. For convenient reference the following table of diversity factors will be useful.

	Residence	Commerical light	Scattered power	Large users
Substation to feeders	1.15	1.15	1.15	1.15
Feeders to transformers	1.8	1.25	2.0	1.25
Transformer to meters	3.0	1.6	1.1	——
Total diversity factor	6.20	2.30	2.53	1.44

From this table it is apparent that the total diversity factor for residence lighting is 6.2, for commercial lighting 2.30, for scattered power 2.53 and for large users of light or power 1.44. The latter figure would apply to consumers requiring from 100 to 500 kw. The combined diversity factor of systems giving all of these kinds of service should range from 2.5 to 3.5 depending upon the relative proportion of each kind served.

These factors may be illustrated by a concrete example:

Assume a residence district, well settled, in which the sum of consumer's demands during the heaviest month of the year is 100 kw. The transformer capacity required to carry the coincident demands of these consumers will be $\frac{100}{3} = 33.3$ kw. The feeder capacity will required be $\frac{33.8}{1.8} = 18.5$ kw. The substation capacity required will be $\frac{18.5}{1.15} = 16.0$ kw.

Similarly, the capacity required for a commercial lighting district in which the sum of the consumer's demands is 100 kw. will be 43.5 kw., for scattered power it is 39.5 kw. and for large light or power consumers, it is 69.5 kw.

This reduction in the amount of capacity required in generating and distributing equipment makes a corresponding reduction in fixed charges which form a large part of the cost of producing electricity. The investment cost is further reduced by the ability to use large generating units which cost less than half as much per kilowatt as the cost of generating machinery in the sizes commonly used for independent plants.

The merging of all these demands has also a pronounced effect on operating costs, in that the load factor of the generating station and distributing systems is very much higher than that of the consumers who take their supply from it. This permits the station to be run at an economical load a large part of the time, thus reducing both labor and fuel cost per unit generated.

The combination of these economies constitutes the central station's justification for existence and it is hardly necessary to add that the justification is well nigh complete in these days of steam turbines and 20,000-kw. generating units.

Thus far the point of view has been from the consumer toward the central station. It is important however that the situation be seen from the point of view of the central station toward the consumer, as the diversity factor has a very marked effect upon the investment accounts which must be carefully considered in determining the cost of rendering the different classes of service.

Stated in the reverse manner for each 100 kw. of substation capacity used to supply residence lighting, the central station company must provide 620 kw. of meter capacity, 207 kw. of transformer capacity, and 115 kw. of feeder capacity. In serving large light or power customers it must provide 144 kw. capacity in meters and transformers and 115 kw. in feeder capacity for each 100 kw. of substation capacity.

The diversity factor for small and scattered consumers is higher than these figures and they require more equipment and a larger investment than is required for the consumers in thickly settled districts.

The investment required per kilowatt varies considerably with the type of construction and the geographical situation of points of supply and delivery. It is considerably more for underground lines than for overhead, and no figures can therefore be given which will have great value for other systems than the one to which they apply.

It may, however, be instructive to give some figures to show in a general way how the investment is distributed between various parts of the system under a set of assumed conditions, which are fairly representative.

Assuming the average cost of a meter at $10, line transformers at $7 to $10 per kw., transformer substations and transmission lines at $35 per kw. and generating station capacity at $150 per kw., the investment is divided approximately as shown in the following table.

It is apparent from these figures that as far as that part of the cost of electricity supply which depends upon investment is concerned, small and scattered consumers are the most expensive to serve. This is due chiefly to the high investment in meters and distributing mains. For instance the cost of meters in residence lighting is about 21 per cent of $820 or $172 per kw.

of station demand. This means that if all the consumers were of this class that the company would have as much money invested in meters as in generating plant.

	Scattered power per cent	Scattered residence per cent	Dense residence per cent	Commercial light per cent	Large users per cent
Generating capacity.........	37.0	18.5	30.0	44.5	60.0
Trans. line and substation....	9.0	4.5	7.5	10.5	14.0
Feeders and mains...........	49.5	52.0	26.0	35.0	23.0
Transformers...............	4.0	4.0	2.5	3.0	3.0
Meters.....................	0.5	21.0	34.0	7.0	negligible
Total................	100.0	100.0	100.0	100.0	100.0
Investment per kw. of annual maximum demand on generating station.............	$410.00	$820.00	$500.00	$350.00	$250.00

The commercial lighting and power business where the diversity factor is smaller and the size of consumers larger, requires less meter investment and more in generating and substation capacity.

The maintenance cost of a large meter and distributing equipment and the general expense items of meter reading, billing, etc., are correspondingly high for small consumers, so that it is probable that the outlying parts of the distributing system are served at a loss during the earlier stages of development.

The study of diversity factors has not been carried out in as much detail heretofore as is desirable. These deductions are presented as a tentative contribution to a subject which has many angles and must submit to revision as experience and more careful observation may demand.

They should in no wise be considered as the last word on the subject as parts of them have been necessarily drawn from sources that could not be thoroughly verified.

It is believed, however, that as a whole, they are sufficiently near the facts to form the basis of intelligent discussion.

A paper presented at the Charlotte meeting of the American Institute of Electrical Engineers, March 30, 1910.

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ELECTRIC DRIVE IN TEXTILE MILLS

BY ALBERT MILMOW

It is the purpose of this paper to deal especially with the employment of electric power, derived from hydroelectric systems of distribution, for the operation of textile mills. It is impossible in a paper of this kind to go very fully into detail, and no attempt will be made to discuss the forms of drives, kind of motors or, in fact, any other technical details, since any one of the more important ones would require a special paper to do it justice.

This paper aims to treat the subject from a broad, general viewpoint, with particular reference to its commercial aspects, and especially in comparison with the old forms of steam drive.

The general branches of the subject which will be taken up are first cost, cost of operation, production as affected by balancing and speed, and general remarks.

First Cost

The references which follow will be to new mills especially equipped for electric drive, insofar as first cost is considered, and not to mills already equipped with steam power. The figures are based on a plant of 25,000 spindles on moderately fine work, which requires a power equipment of about 1000 h.p. The figures which follow are for everything included in a mill that is chargeable to the power plant:

Electric Drive

Group drive throughout, all 2300-volt motors. Power delivered at 2300 volts.

Transformer house and switchboard room	$1,000.00
Belting	1,300.00
Motor support	400.00

Shafting	$8,000.00
Boilers	1,200.00
Boiler setting	350.00
Boiler room	1,650.00
Reservoir	1,800.00
Piping	900.00
Motors	10,560.00
Transformers for low voltage motors, 2 to 5 kw	126.00
Transformers for lighting, 1 to 50 kw	383.00
Switches for motors	300.00
Switchboard	1,500.00
Wiring and installation, including lighting	4,000.00
Freight on electrical apparatus	428.00
	$33,897.00

MECHANICAL DRIVE

Boiler room Engine room Chimney	$16,000.00
Engine, 24-rope wheel, compound	17,500.00
Engine foundation	2,000.00
Boilers	6,000.00
Boiler setting	1,800.00
Smoke breeching	770.00
Condenser, pumps and heaters	2,520.00
Reservoir and crib	6,500.00
Steam power piping	6,000.00
Ropeway and extra sprinklers	2,000.00
Shafting and structural steel work	12,053.00
Rope	600.00
Belting, main drive and counters	1,300.00
Lighting generator, belted, and switchboard	1,000.00
Marine engine generator, 10 kw., and switchboard	1,000.00
Lighting wiring, 2-wire system	2,000.00
Total	$79,043.00

From the table it will be seen that the total cost of the power plant for steam drive would be $79 per h.p., while the cost for a similar electric equipment is $33.90 per h.p., or a saving of $45.10 per h.p. of plant capacity where the electric drive is used.

It is to be noted that all costs are included in these estimates, though it is quite usual for advocates of steam drive to take for its first cost only the costs of engines, boilers, piping, etc., neglecting such important items as building chimneys, belt-ways, condenser reservoirs and other items which are essential to steam drive, but which are not required where a mill is electrically driven. This difference in cost should enter into the cost of power, taking the interest and depreciation at 12 per cent, the lowest possible figure. However, it is obvious that if this same amount of money were expended in producing textile machinery the earnings would certainly exceed the 6 per cent included in this figure as an interest charge.

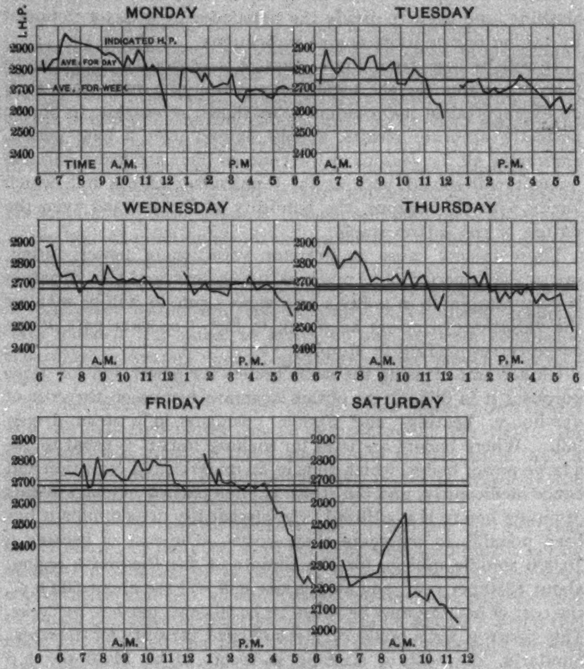


FIG. 1

COST OF OPERATION

The cost of steam power in a textile mill is very difficult to determine. Fig. 1 shows a series of engine indications made for a period of one week, at ten minute intervals. It will be noted that a very wide variation of power is shown and only a very thorough and detailed set of indications, as shown here, will give a fair average of the amount of power.

It is customary with advocates of steam drive to make certain large deductions in a purely arbitrary manner from the total cost, for the values of steam used in processes of manufacture other than for power, such as dye-house operation, heating and slashing, and then to divide the remainder by a factor obtained by taking one or more engine indications.

It will be seen from Fig. 1 that it is obviously erroneous to take any value for the total horse power of a mill other than an average taken approximately as shown; even this, to obtain perfectly accurate results, should extend over a long period, embracing all the seasons of the year, as there are many variable quantities involved, such as the temperature of the mill, which varies with the seasons, the humidity of the air, and even the nature of the cotton staple.

These factors cause an extreme variation of power during, say, a year's period of as much as 20 per cent, and this variation is very noticeable in a day's or a week's run, as will be seen by the variations of power as shown in Fig. 1 on that part of the curve corresponding to Monday.

On account of using the same boilers for power and for other purposes it is difficult to obtain accurate figures on the cost of dye-house, heating, and slasher operation in a steam-driven mill. Where boilers are used for making tests it is usual to use a large power boiler, which runs in an underloaded condition and hence inefficiently, and the steam is often carried in long systems of piping before it is utilized. In electrically driven mills it has been possible to segregate these costs. The cost of heating a 10,000 spindle mill is, for the climate of the Piedmont region, about $250 per year, and as this size mill will use about 500 h.p., the cost of heating may be taken to be 50 cents per h.p. per year. This figure is for a boiler of just sufficient capacity for the work. Similarly, the cost of slashing is found to be $1.40 per h.p per year, or a total of $1.90 per h.p. per year for heating and slashing. Of course, this figure varies with the class of work, but it applies to work using an average of about No. 30 yarn. The figure commonly taken in estimating steam horse power cost is about $4.00 per h.p. per year, which is entirely too high. For these reasons it is very difficult to determine any accurate cost of the steam power on the horse power-year basis.

In dealing with about seventy mills electrically driven, many of which have been converted from steam to electric drive, it is found that no two present identical conditions, and even when a mill is changed to electric drive, the opportunity of improving speeds, etc., is usually taken advantage of, and the mill is generally reorganized to an extent that precludes the possibility of a direct comparison.

It has been found, however, that where the machinery in a converted mill has been kept intact and the speed kept constant, and where accurate records of engine indications prior to the change have been kept (which is rarely done) a saving in the power required is effected, though most mills when making this change take the opportunity afforded of improving production in one or more ways and thus increase the power required. The manner of operating a mill is also important in determining the amount of power required. Some mill men force production to the highest point, while others are content to run at moderate speeds and production.

The varying cost of fuel, the quantity and varying temperature of condenser water, and the difficulty of obtaining accurate data make it impossible to arrive at any accurate conclusion regarding an average cost of steam-generated power in textile mills.

In electrically-driven mills the absolute horse power-hours and the indicated power can be determined at any time. An opportunity is given to check wastes and correct them, and a considerable amount of non-productive power is saved by the elimination of useless shafting.

Assuming the price of electricity to be $25 per h.p. per year for 11 hours per day, 306 days per year, and assuming a saving at equal production of 15 per cent in power, which I consider conservative, the cost at which steam power must be generated to equal the price of electric power will be $21.25. From this must be deducted the fixed charges on the difference in first cost, which we may take at 12 per cent on $45.10, or $5.41 per h.p. per year, leaving $15.84, plus $1.90 which will be required for the heating and slashing operations of the mill, or a total of $17.74 as the figure at which steam power must be generated to be equal in cost to electric power at $25 per h.p.; and in this figure there must be included the cost of all oil, waste, labor, fuel, ash removal, coal handling, superintendence and, most important of all, the item of repairs, which is frequently omitted entirely in making estimates of steam power cost. If it were possible to attain this figure with a steam drive, a power only evry inferior to electric drive would have then been obtained.

PRODUCTION

Hydroelectric power offers many advantages in operation, due to the readiness with which parts of a mill may be run so that the maximum possible output may be obtained. By reference to Fig. 1 it will be noted that a wide variation of power is shown, due, among other things, to the fact that it is unnecessary to run all of the departments all of the time.

In a mill which has perfect balance, each piece of machinery used in each process will deliver to the next succeeding department just the right amount of material to keep both sets of machinery operating at full output all the time, and so on until the completed article of manufacture is produced. This is a condition difficult to realize, as in actual service it is found that market conditions in nearly every case make change of product necessary, and in a mill which can be designed for only a limited range of work, any variation from this affects all the preparatory departments by giving them more work for coarser product or less for finer product.

In mills which are used exclusively for spinning, and which do no weaving, a part of the product is in the form of twisted yarns and part of it in single yarns; hence the twister department, which uses a great deal of power, is often called upon to its full extent and again is often entirely idle.

In equipping a mill for electric drive it is usual and proper to provide one or more motors for each process of the work so that in case the demand on that department is increased, it is possible to work over time on that particular department, where, on account of the inefficiency of the engine at light loads and often because of the very small part of its capacity that is required, it would be impossible to run with a steam drive; or if some department, such as the twisters, is not needed at all, the motor provided for it can be shut down entirely, saving all expense of its operation without affecting the operation of any other department or in any way affecting its speed.

These points are actually taken advantage of and practiced to a very great extent. In mills using automatic looms they are frequently left in operation at the noon hour, when they will run until some threads break, when the loom automatically stops itself and remains stopped until the weaver returns. Many of them continue in operation without interruption. In some cases looms are left in operation after shutting down time until the loom stops itself, which often does not occur until all the filling yarn is exhausted. These hours in the aggregate sum up a very respectable total in the course of the year.

The textile industry in the south is at a growing stage and few if any mills are left complete as first installed, especially among the larger mills. It is almost the usual thing to see a mill with one of its ends boarded up instead of closed with brick, thus proclaiming to the world the intention of its owners to extend it as soon as they can. In the days before electric power was available this necessitated a steam plant entirely too large for the first installation, so a plan was resorted to of installing one-half of an engine and operating this as a simple engine, with the ultimate intention of adding a cylinder for compounding when the mill should be increased. This arrangement necessitated the investment of a great deal of money in a steam plant to begin with, which to-day can be put into the manufacture of cotton goods, and resulted in very high costs for power when using only a simple engine. These conditions have too often proved a handicap which has prevented the mill men from realizing their hopes as soon as they might have done. With electric drive the system is perfectly flexible. Only the investment for the work actually installed is demanded at the outset, and the full output and efficiency are secured from the beginning.

An interesting application illustrating the flexibility of electric drive has recently been made and is being quite generally followed. In this case a mill was built with a capital of $100,000 and with an equipment of 5000 spindles for the production of yarns. It was the intention to operate this mill day and night and the promotion of the mill was based on this idea. It was found, however, that for the spinning frames, which require women and girls to operate them, sufficiently satisfactory labor could not be obtained to operate during the night run, so that the management found itself in a position of being able to offer to its stockholders a production based only on the actual money employed, or $100,000. Through their own initiative they then took advantage of the opportunity offered by electric drive and added to their equipment an amount of spinning machinery equal to that already installed. This operated with the rest of the equipment during the day time, and all preparatory machinery, for which only men are employed, is operated day and night, thus giving material to the double number of spinning frames during the day. This resulted in a production equal to that of a mill of 10,000 spindles costing $200,000, while the total cost of the mill was only $120,000. The addition of the extra spinning machinery cost $20,000, and the original cost of the mill was $100,000. This arrangement has, simply by the proper use of electric power, saved the mill an additional burden of investment of $80,000, the interest and also the depreciation on which would more than eliminate the entire power bill.

The old idea of building a mill amounted essentially to first building a steam plant and then building the mill to conform to it, as its shape and the arrangement of the machinery had to conform to the most convenient ways of running shafting. In an electrically driven mill the matter of power is secondary. The machinery is placed in the most convenient way for operation as a textile plant and the motors are installed afterwards.

It has been found that in practically every mill that has been converted from mechanical to electric drive, an increase in production has been obtained. This is almost always the case and it is not usually taken account of by investigators of power costs. Among the uninformed there is a quite general opinion that the converted mill takes to operate it electrically as much as or more power than it previously did with steam. On account of the increased production with the electric drive this is true in a great many cases; but in many other cases it is uncertain, as no accurate records of steam indications have been taken or kept. The explanation of this increase in power is simply that the production has been increased. At the time the motors are installed the speeds of the mill are readjusted and nearly always increased, the power is applied more directly to the work with less chance of slippage of belts and, above all, the speed with motor drive is much more constant.

Figs. 2 to 51 show a series of curves taken with a delicate recording tachometer. The longitudinal lines each represent 1 per cent of instantaneous variation, and approximately one-half inch in length of the diagram shows an interval of time of one second. All of these charts shown were taken in actual service, excepting Fig. 6, which was taken to prove the accuracy of the instrument with the best known constant speed drive—a direct-current shunt motor supplied with current from storage batteries.

Fig. 2 shows a chart from a 3000-h.p. cross-compound engine, taken directly from the main driving shaft.

Fig. 3 shows one from a 1000-h.p. cross-compound engine.

Figs. 4 and 5 are charts taken directly from the shafts of an 85-h.p. and a 125-h.p. motor, respectively.

Fig. 6 is taken from a known constant speed.

Figs. 7 and 8 are from water turbines in operation and under load.

Figs. 9 to 15 inclusive show speeds of a shaft directly driven from one large engine through rope drives, with the exception of Figs. 10 and 15 in which the shafts were driven from a second belt. Fig. 10 is the record of a shaft driven by a belt from the shaft recorded in Fig. 9, and Fig. 15 a shaft belt-driven from that of Fig. 14.

Figs. 16 to 20 show the same shafts driven by motors after the mill has been converted. Figs. 9 and 16, 10 and 17, 11 and 18, 12 and 19, 14 and 20, 15 and 21 represent steam and electric drives, respectively.

It will be seen from these records that a very material improvement in initial speed and transmitted speed has taken place. This mill was selected, among many others, as being representative of a large well equipped mill, and the steam drive is much worse in many of the mills charted.

Figs. 22 and 23 are of particular interest as showing the torsional spring in the shaft. This represents a line of shafting about 300 feet long such as is commonly found in weave rooms. Fig. 22 was taken at the driving end and Fig. 23 at the extreme other end, showing that where the original speed was excellent it was badly perturbed before reaching the end of the shaft.

Figs. 24 to 32 show speeds in a steam driven weave room. Fig. 27 is taken with the engine drive and the others are counterbelted to the shaft in Fig. 23 on one side, and to that in Fig. 32 on the other. It will be noted that the original speed, which was good, has been increasingly perturbed by belting, so that the greatest variation in every case is shown on the last shaft. Figs. 33 to 41 show speed records of the same shafts driven by two large motors. It will be noted that a considerable general improvement has taken place.

Figs. 42 to 44 show very badly perturbed speeds. These represent the three main line shafts on which the entire machinery of a large mill depends. This speed variation is caused by bad belting and excessive end play in the shafts, causing crowning and slackening of the belts alternately.

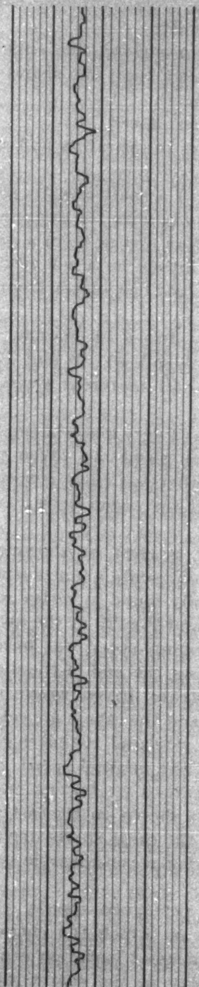


Fig. 2

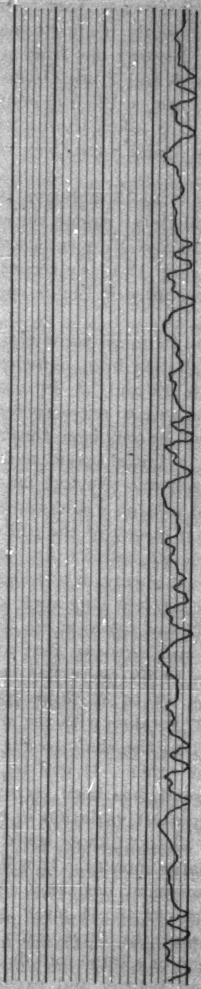


Fig. 3

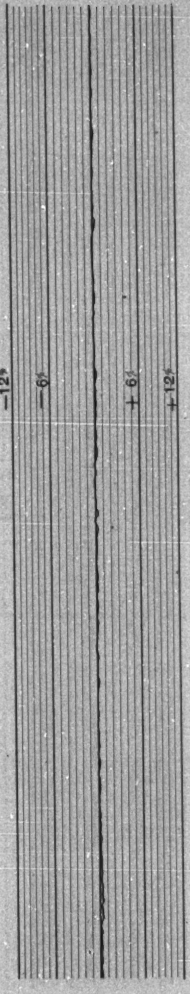


Fig. 4

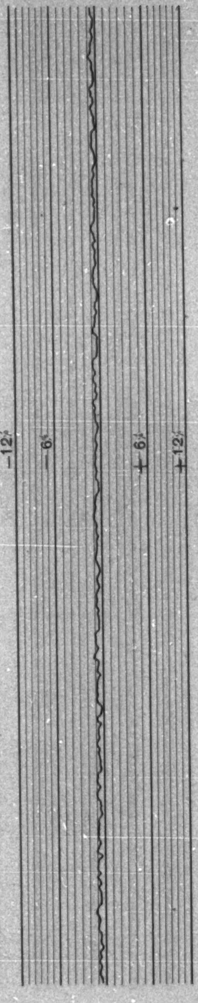


Fig. 5

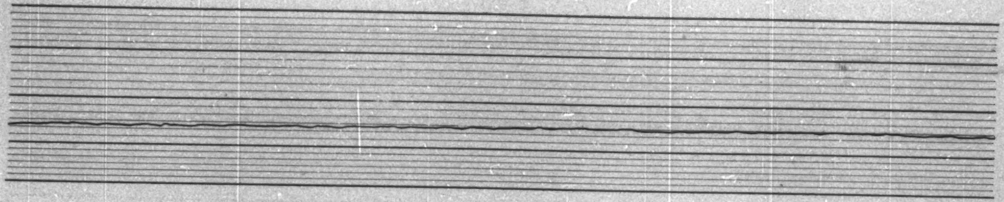


Fig. 6

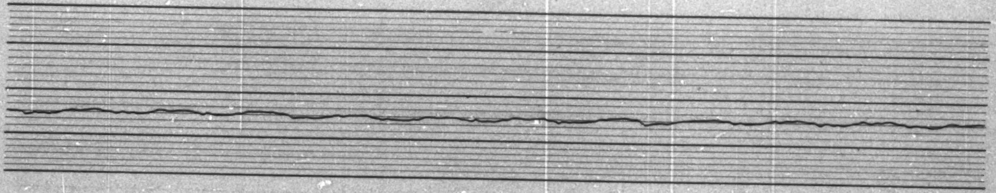


Fig. 7

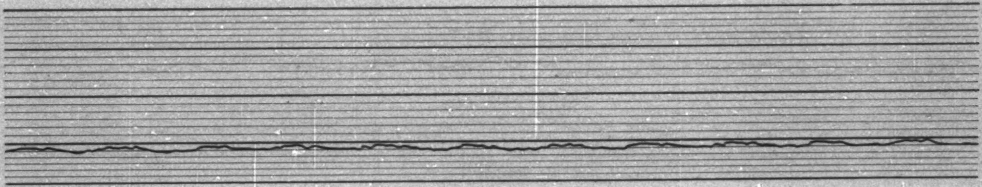


FIG. 8

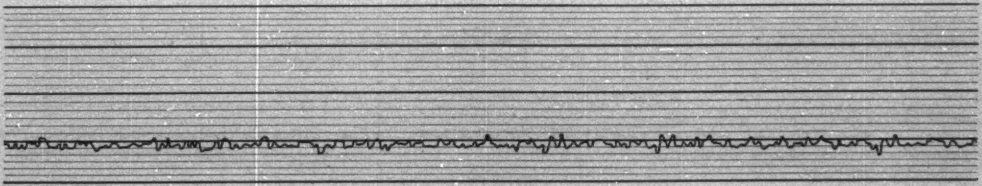


FIG. 9

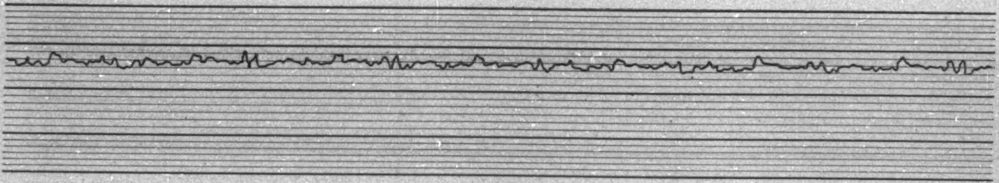


FIG. 10

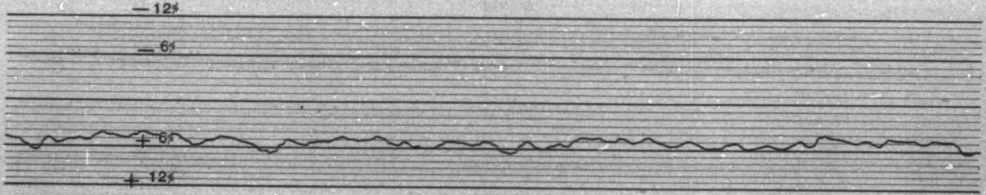


FIG. 11

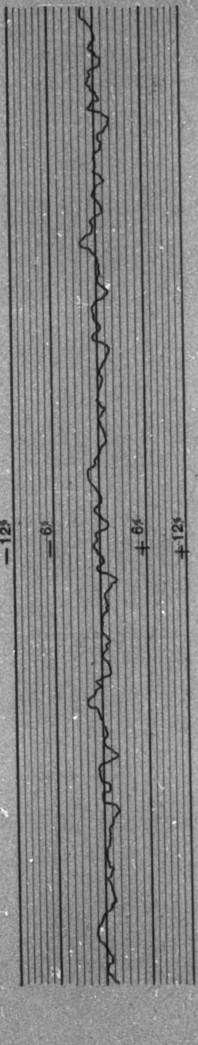


Fig. 12

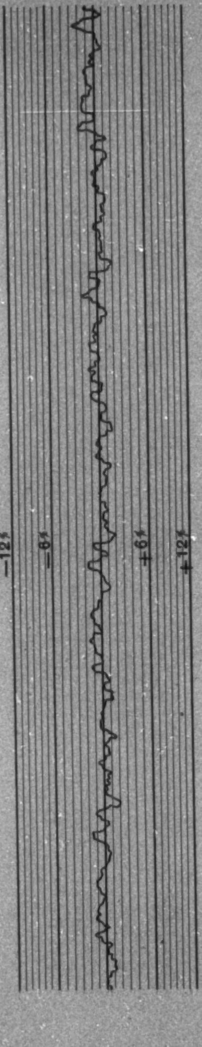


Fig. 13

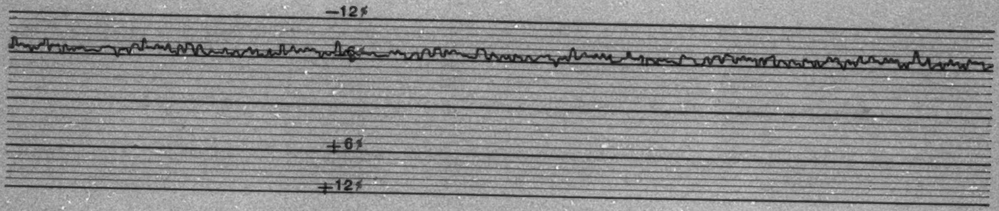


Fig. 14

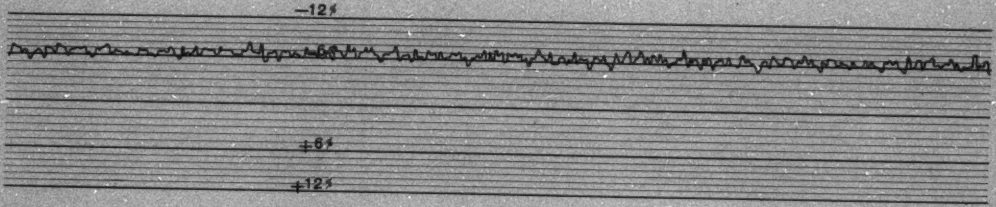


Fig. 15

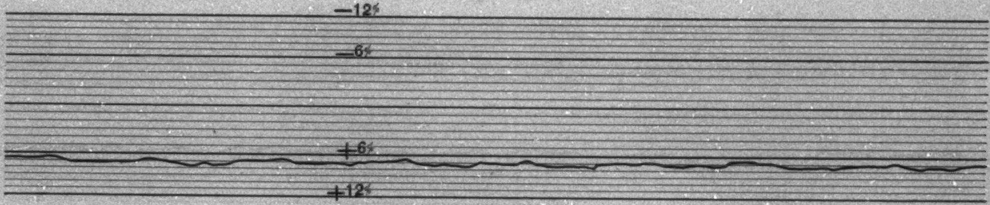


Fig. 16

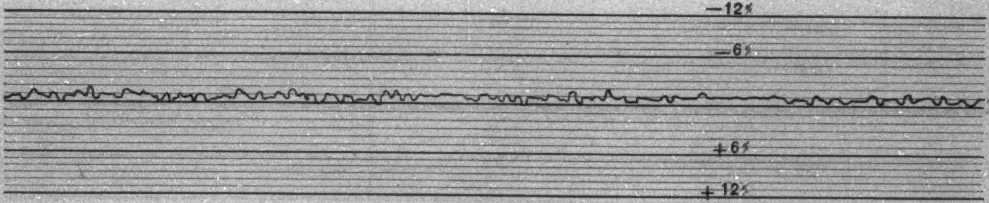


Fig. 17

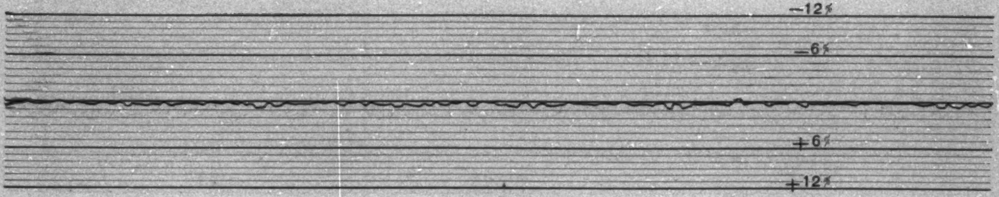


Fig. 18

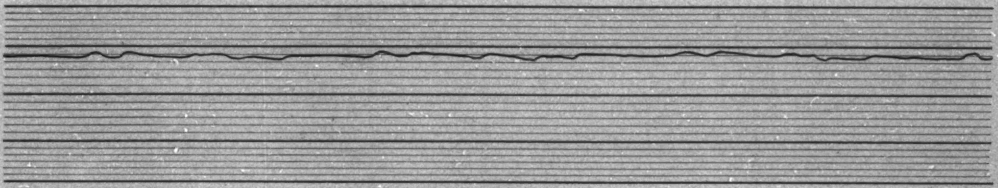


Fig. 19

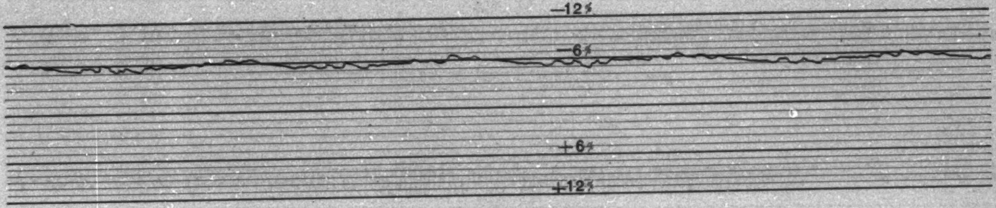


Fig. 20

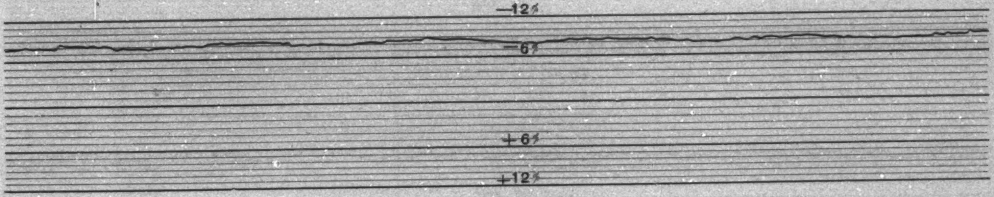


Fig. 21

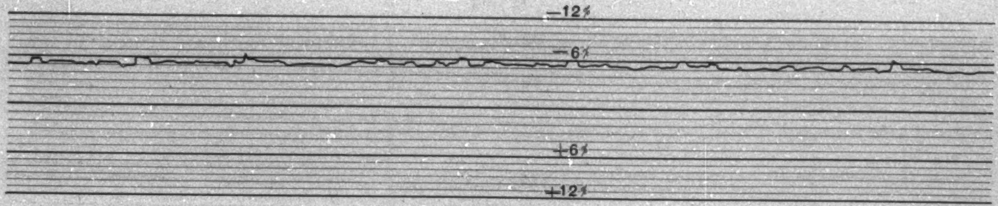


FIG. 22

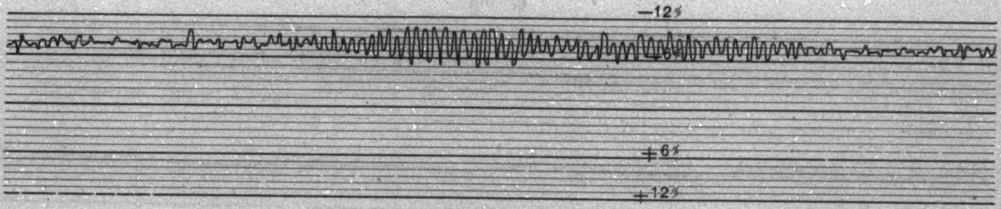


FIG. 23

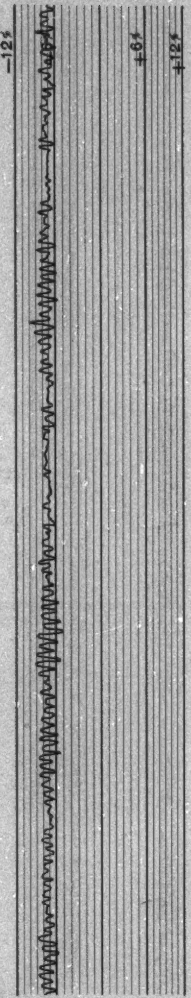


Fig. 24

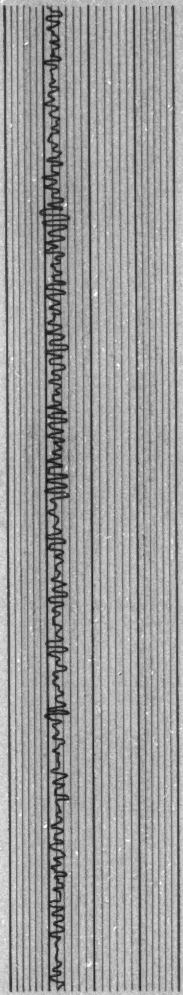


Fig. 25

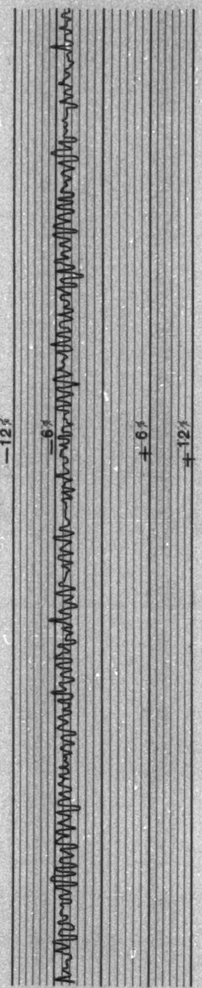


Fig. 26

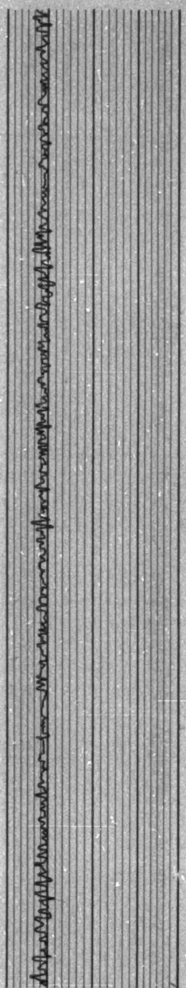


Fig. 27

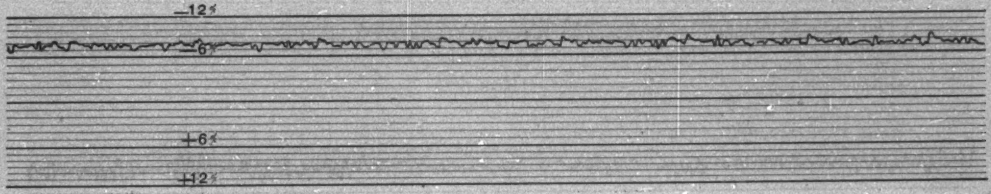


FIG. 28

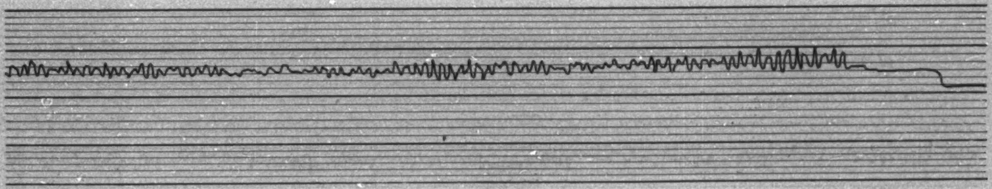


FIG. 29

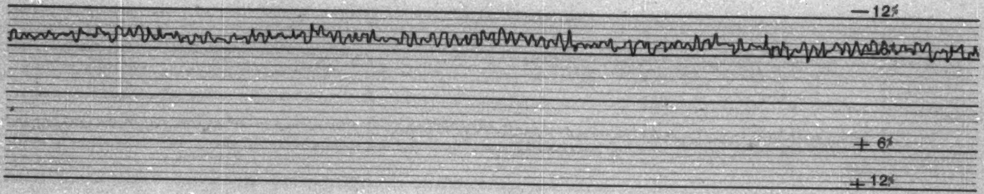


FIG 30

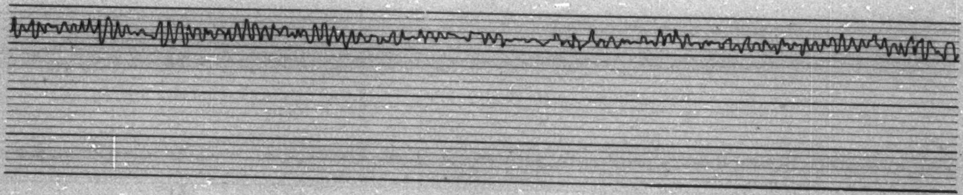


FIG. 31

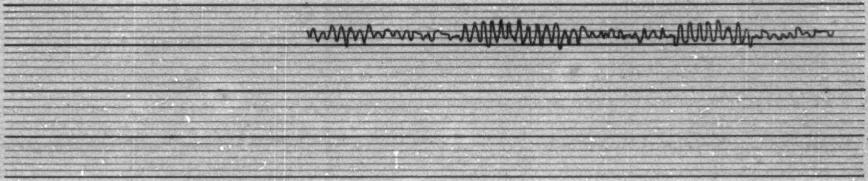


FIG. 32

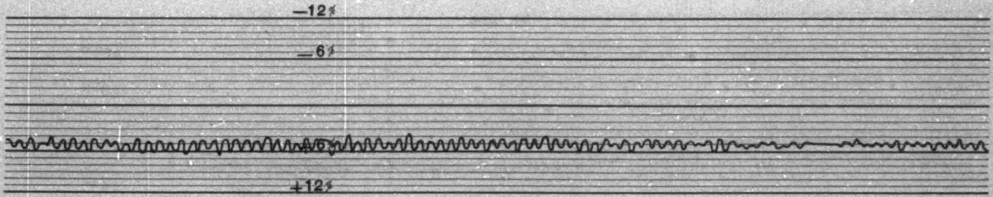


FIG. 33

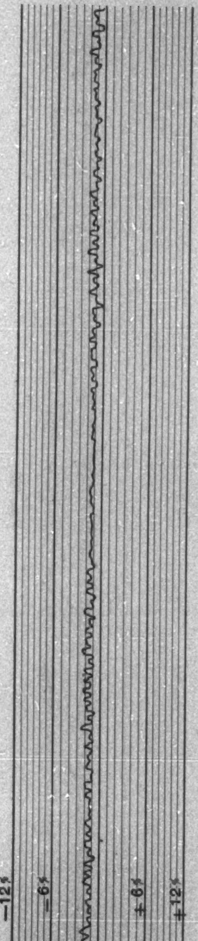


FIG. 34

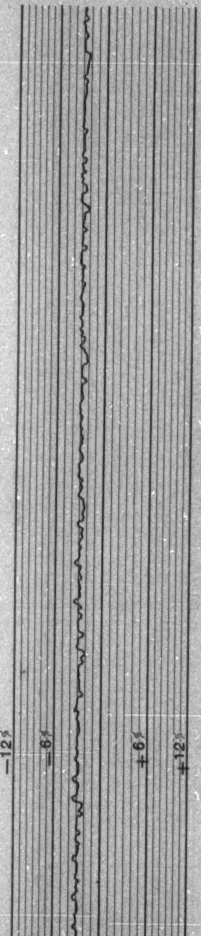


FIG. 35

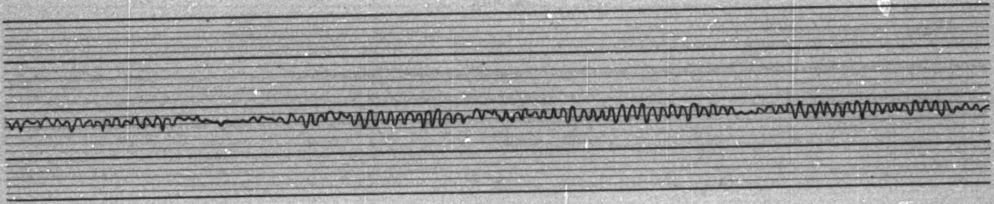


FIG. 36

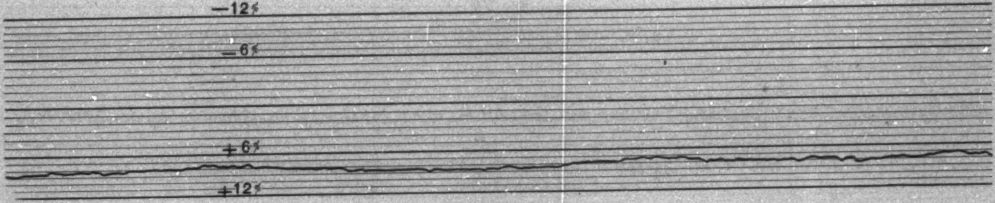


FIG. 37

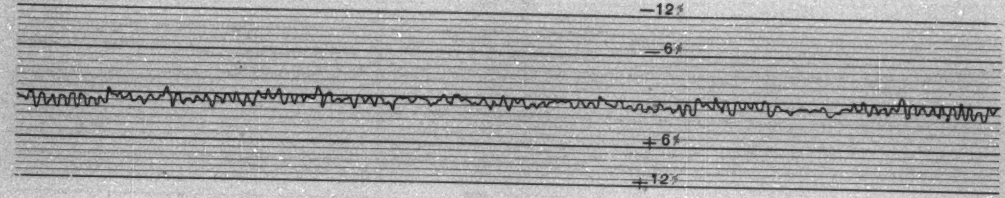


FIG. 38

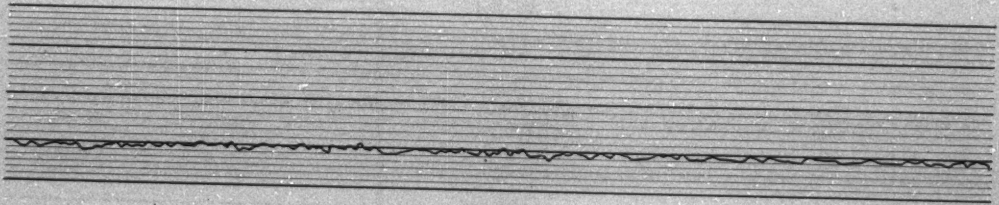


FIG. 39

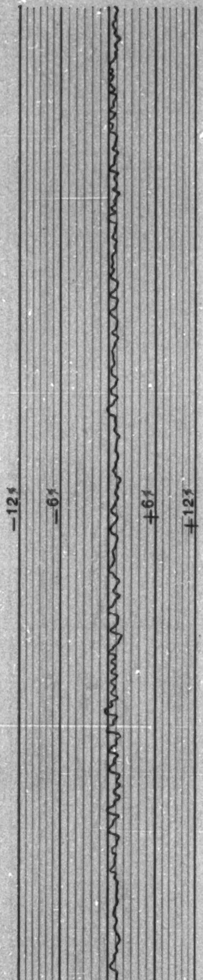


FIG. 40

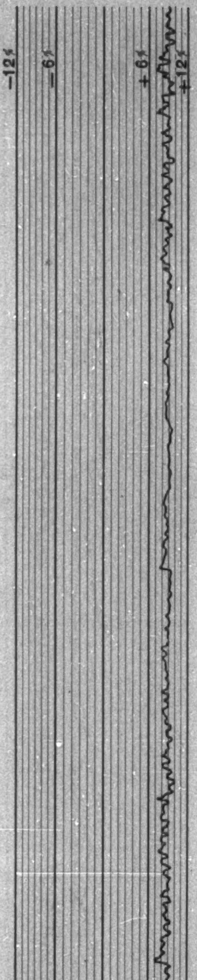


FIG. 41

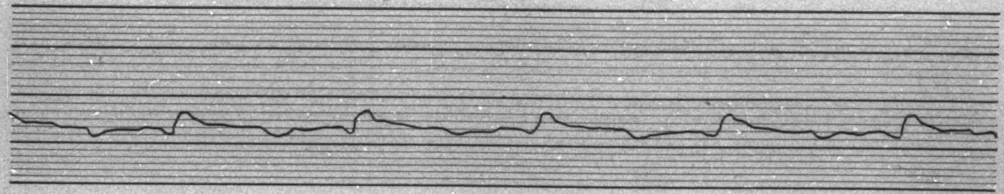


FIG. 42

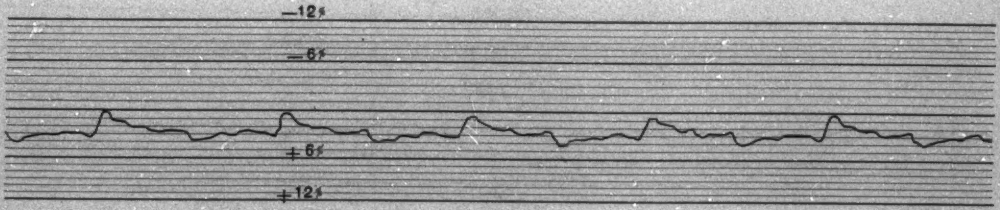


FIG. 43

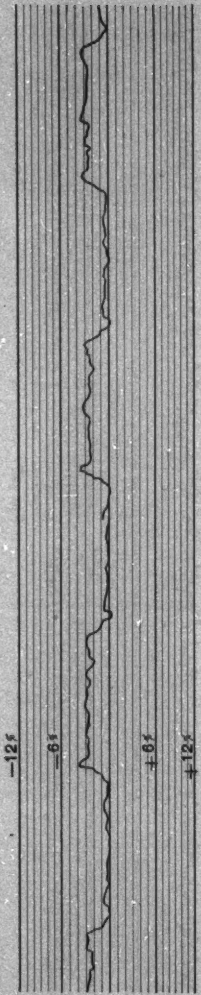


Fig. 44

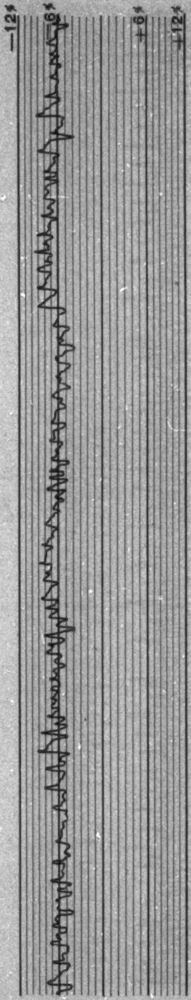


Fig. 45

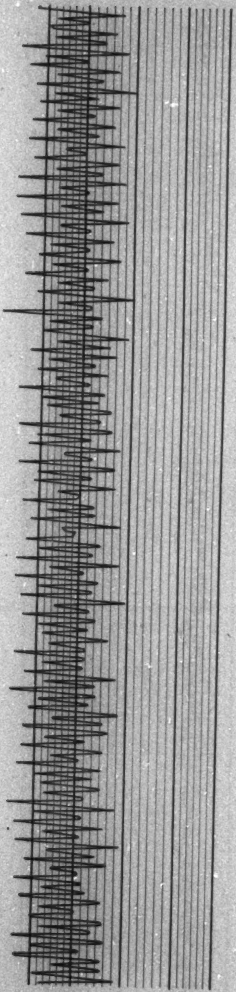


FIG. 46

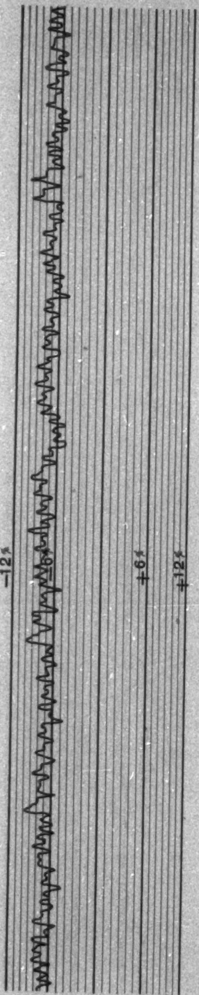


FIG. 47

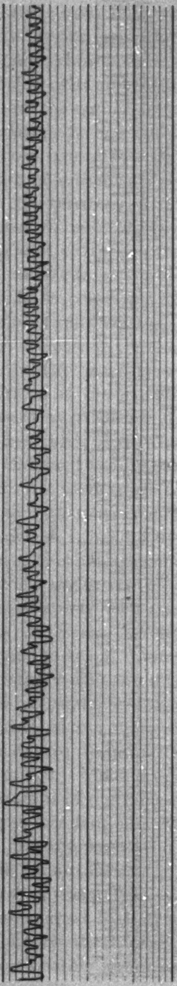


Fig. 48

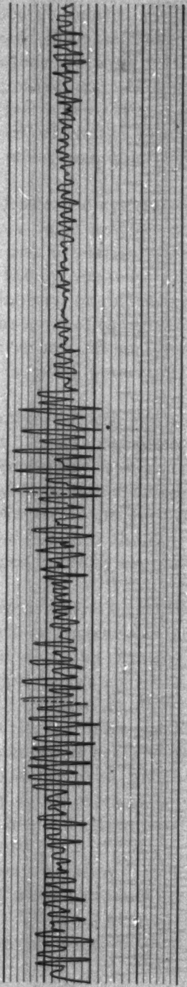


Fig. 49

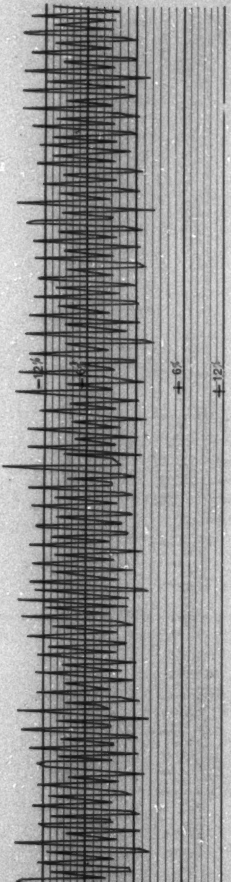


FIG. 50

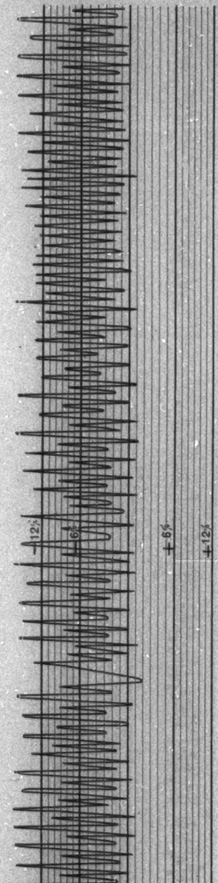


FIG. 51

These curves show the insufficiency of counted speeds where instantaneous variation is neglected. The highest point of the curve shows the maximum at which the work will run and all below that represents a loss of production. As a matter of interest the curves, Figs. 45 to 51, are shown. These illustrate an extremely bad speed condition of which the mill manager has been ignorant, and the mill has never been able to get out a good production.

In the territory of the larger hydroelectric systems the total number of mills operated consume a large amount of power. Each mill comprised in the group uses a relatively small proportion of the power furnished by the system. It is therefore possible to throw off or on many motors, or, indeed, many of the entire mills without disturbing the speed of the system. This is not the case in a mechanically driven mill, where even a small part of the machinery represents a good percentage of the total load of the engine.

In a converted mill, driven from a hydroelectric station, one of two results are always brought about. If the original production is maintained the amount of power necessary is reduced. This should not in all cases be regarded as of paramount importance, the most vital advantage being an increased product from the mill, which it has been shown can be obtained through electric drive. This has actually been obtained in nearly every case that has come under my observation.

In mills only very roughly converted, where surplus power is taken, and where the old uneconomical arrangement is left intact so that the steam drive may be used when the electric power is temporarily shut off, all carefully kept records show that an increase of production of from 2 to 10 per cent is obtained. In new mills especially constructed for electric drive the higher of these figures should obtain. This increase is brought about by two things. First, proper balancing of the work, and next, the application of motive power directly to the work it is to drive, and the fact that this motive power has a constant speed value, both instantaneously and continuously.

The importance of production may be shown in a broad, general way as follows: The value of a mill's product per annum is about equal to its capital stock. The cost of manufacture, with many variations for the class of work, may be taken proportionately about as follows:

Cotton, 60 per cent; power, 4 per cent; all other costs, 36 per cent, and the power cost, as a total is from 3 to 6 per cent of the total market value of the product. Thus, assuming the cost of a 5000 spindle mill as $100,000, its product in a year will be worth, roughly, $100,000 and its power bills say $5,000. If the product of this mill could be increased 10 per cent the gross value of this increase of product would be $10,000 of which the only cost would be cotton and power and some labor. The most costly operations of labor are paid by the day and effect no increase.

Allowing, however, for some increased labor cost we have as the total cost of this extra production:

Cotton, 60 per cent; power, 4 per cent, and labor, 3 per cent, or a total of 67 per cent and a net profit of $3,300 per year, or two-thirds of the total cost of the power, thus nearly eliminating the power bill. On account of the steadiness of the speed of the electric drive the machinery will suffer less deterioration than if run at even lower speeds with the steam drive.

It is very proper and very necessary to take all of these points into account as having a direct bearing on the cost of steam power.

General Remarks

Fig. 52 shows the increase in power furnished to textile mills in the Piedmont region of North Carolina and South Carolina by the Southern Power Company. It will be seen from this that the increase was very slight during the years 1904, 1905 and 1906. In 1907 the mill managements in the territory where these lines existed having had the experience of their neighbors over the years previously referred to, began to appreciate the advantages and economies of the hydroelectric drive. It will be noted from this curve that during the year of 1909 and especially the last six months this increase has been greater than at any other time.

In hydroelectric systems of distribution to cotton mills it is found to be impracticable to place a sub-station for each consumer, especially to meet the conditions which we have in Piedmont Carolina, where several mills of small or moderate size are installed in one town. This is on account of the large first cost of a substation reducing from 100,000 volts, and also on account of the difficulty of running the high-tension mains through cities and towns. On account of the high cost of transmitting low secondary voltage any distance, both as to initial investment and in power loss, it was found necessary to adopt 2200-volt motors in mills where the general practice had been to use motors of 550, 400 and even as low as 220 volts.

At first considerable prejudice existed among the mill owners and the underwriters against the use of high voltage motors, but some years of experience have demonstrated their superiority in every way. The first cost is about equal to that of the lower voltage motors. Their efficiency is equal and the slip is also equal or somewhat less. With an equipment of 2200-volt motors power can be transmitted with an economical loss and reasonable first cost to a distance of approximately one and one-half miles from the central sub-station.

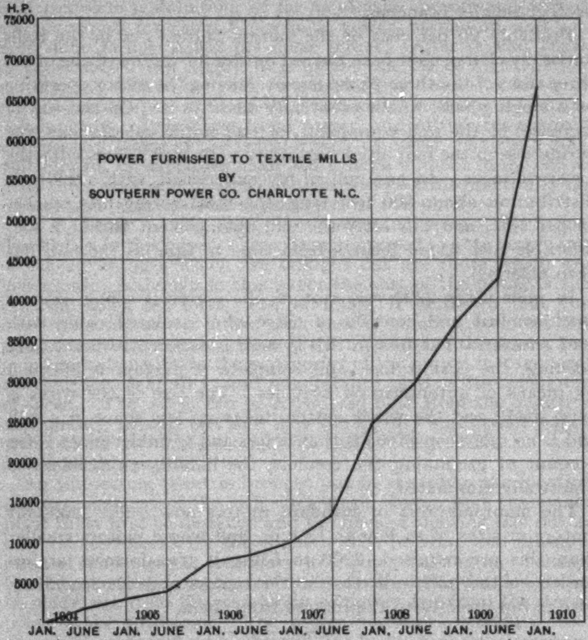


Fig. 52

In many of the older low voltage installations, for the sake of economy, open wire is run in the mill. The cost of installing it in conduit would be excessive on account of its size. And also on account of the size of the wires, and the very extensive system of feeders, it is only a matter of time until open wiring becomes disarranged, due to its being swept to remove the lint and dirt which it accumulates. Another serious feature of this system is the frequent and necessary employment of fuses to protect smaller branches.

Probably 90 per cent of the motors burned out in the mills under my charge have been burned out by the failure of one of the three fuses of the three-phase circuit, leaving the motor operating on a single phase, which eventually destroys it. On account of increases to the mill equipment, or bad initial calculations, the wiring loss in the mill often runs up to very high figures with the lower voltages. In one mill in my experience, with a 220-volt distribution about 500 feet long, the total wiring loss reaches 15 per cent, and this after the mill management had at a considerable cost added feeders from time to time as the mill has been enlarged.

In mills using 2200-volt motors, the wiring is run in iron or steel conduit and consists of three-wire insulated cable with lead sheaths. The loss in this system is reduced to practically nothing, the cost is low, and complete protection is afforded by means of automatic oil switches. The size of the wires is very small, and the whole system takes up less space in a mill and is no more conspicuous than water and sprinkler pipes. On account of grounding the conduit, the liability to accident is practically eliminated.

The manufacturers of standard motors now build 2200-volt motors in sizes of as low as 15 h.p., and where motors smaller than this are required, 2200 to 550-volt transformers are installed on the mill wall close to the motors and the secondary wire is run directly to the motors from them.

DISCUSSION ON "ELECTRIC DRIVE IN TEXTILE MILLS", CHARLOTTE, N. C., MARCH 30, 1910.

Mr. Milmow: In reference to the first cost of electric drives, we have taken the figure at $33 per horse power, which includes a great many things ordinarily not required in the electrical equipment of the mills. The $33 includes all the shafting and belting, fire protection, and reservoir, and other things of that kind. A new mill can be equipped, or an old mill converted, as a complete installation, as far as electric motors and wiring are concerned, for about $15 a horse power, maximum, and has been done as low as $12 per horse power. After several years of experience I can highly recommend the use of high voltage motors, and wish to say that we consider that the use of 550-volt motors handicaps a mill at the start and handicaps its future development. It requires more power, and introduces entirely unnecessary losses in the transforming of power, but the 2,200-volt motors, of which we have had a large number in use, have done their work and carried out their service with practically no repairs and with general satisfaction to everybody.

C. F. Scott: Aside from the particular points which are dwelt upon in this paper, I have been interested to note how many of the advantages which are brought out are those which are incidental. Although in this paper the cost of the power is the essential thing set forth, and although it is shown that the cost of electric power is less than that of steam power, yet the great advantage does not lie in the simple cost of the power, but in indirect elements; in the superiority of the motor, in its general convenience, flexibility, and adaptability, and in its constancy of speed. The power can be considered both from the quantity and quality standpoints and it is the quality standpoint which seems to me to be the strong one, and the important one, as is stated in this paper.

An interesting point is brought out in regard to the location and arrangement of the mill—in a steam-driven mill the steam plant must first be designed and the lines of shafting laid out as may be convenient for the engine. The building and arrangement of machinery is secondary to engine, shafting and belting. On the other hand, in the electrically-driven mill, the design can be made, not from the standpoint of power, but from the standpoint of the operations. The power becomes secondary, and the whole arrangement of the mill can be made most economical and most serviceable and efficient, so as to better serve its real purpose of economic production. The mill itself can be installed in any convenient place without reference to waterfalls or convenient proximity of condensing water, and the motor can be put up on the ceiling where it will take no room. Further this paper shows an increase in production by the gain in speed constancy. These indirect things make for better and larger production through the higher efficiency which can be gotten from the operation of the mill and the labor which is there employed.

In the study of a problem of this kind, we have a most excellent illustration of the advantages attained by taking a broad view of the situation. We find here, as in many other cases, that the indirect advantages in the use of electricity, may be of far greater value than simply the saving in the cost of power.

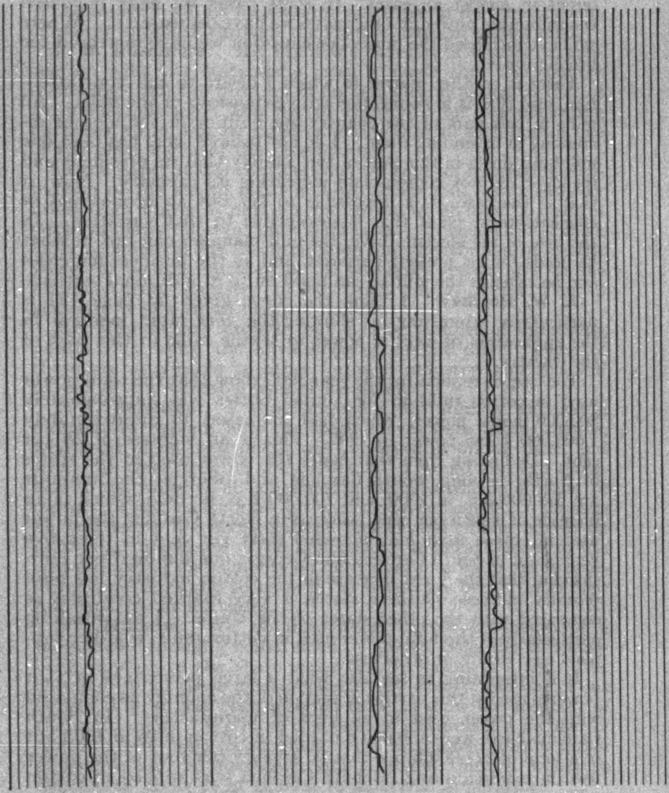
W. S. Lee: If you will refer to the chart on page 387, which represents a curve taken by indicating an engine every ten minutes for a period of one week, you will find a rather interesting condition of affairs. That is one of the best and most economical mills in the whole territory. You will note that on Monday morning the mill began with a very heavy load, something over 2900 h.p., and that this load ran fairly steady during the forenoon, but in the afternoon dropped off considerably. This same condition obtained on Tuesday. I call your special attention to the last few hours on Wednesday. I ask you also to note the last hour on Thursday, and the last hour and a half on Friday. These curves present a graphic picture which shows that the mill is not being operated up to the proper efficiency. The production of the mill was decreased, due to the fact that each department was not kept up to the highest standard of efficiency, as it did not work its full number of hours per day. This shows the importance of keeping a power curve, which will show what the mill is doing. A manager can tell from his power curve whether the mill is being run properly.

I do not know that I can explain this subject of speeds more thoroughly than is done by these curves. Speed means a great deal in output to cotton mills. Cotton mill machinery is built to operate automatically. If a thread or any part breaks it stops the machine automatically and it takes a certain time for the operator to get to this machine and get it started. Furthermore, the momentary variations in speed cause certain pulsations which, when magnified, produce a cadence throughout the mill. These pulsations very often break thread and stop the machine, which normally would not occur if the speed was more uniform.

I want to call your attention especially to the charts on page 418. These are from a mill with which we have a contract to furnish power; it is now operated by steam and has a speed variation of 16 per cent. If you will put an ordinary tachometer on the end of the shaft, and take speed for one minute, it will show good speed, but this does not show the variation up and down as shown by this curve on a large scale. The variation from the average speed is eight per cent below and eight per cent above.

Since the charts referred to on page 418 of Mr. Milmow's paper were taken, showing variation of this mill while being driven by steam, the mill has been electrically equipped and is now operating by electric power. Chart No. 1 shows a 60-h.p.

motor in this same mill driving cards; chart No. 2 shows a 60-h.p. motor on spinning frames; chart No. 3 shows an 85-h.p. motor on spinning frames. By observing these charts it will be noted that the extreme variation is from 2 per cent to 3 per cent, and most of the time less.



No. 1 No. 2 No. 3

If you can use a power in the mill that will have only three per cent speed variation, you immediately move your average speed up six-and-a-half per cent higher than you had it before. If you move the speed up six-and-a-half per cent, we know more goods are made, and we know it takes more power to do it. The results of changing over a lot of these mills have been different in almost all cases. In some cases we have increased the amount of power, in other cases we have decreased it. Where we have increased the power consumption we have increased the production.

There is another matter to which I desire to call your attention, and that is in connection with extensions of the mills. All mills in this part of the country are built with the idea of increasing or extending them. I do not believe there has been one mill built down in this part of the country that its president and manager did not contemplate increasing its capacity. Now, if that is the case, it is impossible to lay out an economical or efficient steam plant that is susceptible to that variation. In the case of the electric drive, the mill manager can put in what he needs for his present purposes, and as the business increases and he extends the mill he can build on to it additional sections.

A. W. Henshaw: I think the curve given on page 421 is particularly interesting, as showing the very rapid increase in the application of electric power to textile mills in this part of the country.

The Census reports for the year 1900 show that the total power used in cotton mills in the United States was approximately 800,000 horse power, which had increased to approximately 1,000,000 horse power in 1905. This is an increase of 28 per cent. Deducting from that figure the power used in the states of North Carolina, South Carolina and Georgia, the amounts are 628,000 h.p. in 1900, and 700,000 h.p. in 1905, which is an increase of eleven per cent; whereas in North Carolina the power used in cotton mills had increased sixty per cent in these five years, and in South Carolina and Georgia one hundred per cent, showing that the great increase in the cotton industry has been recently in these southern states, a very marked condition as compared with the other states of the Union. I am speaking particularly of the total power used in cotton mills, whether supplied electrically or otherwise.

It is interesting to see also what a large percentage of that power is used in this particular section of the country as compared with the power used in all lines of manufacture. In South Carolina there were 156,000 h.p. used in cotton mills in 1905 out of a total of 221,000 h.p.—that is, seventy per cent of the power used in manufacturing in South Carolina was applied in cotton mills. In North Carolina there were 93,000 h.p. used in cotton mills, out of a total of 219,000 h.p., which is 42 per cent.

The amount which is applied by the use of electric motors has increased very rapidly, and is continuing to increase. The State of South Carolina has been far ahead of any of the other states in that respect. In 1905, approximately 19 per cent of the power used in cotton mills was applied by the electric drive, and in North Carolina only about two per cent. That there has been a very rapid increase since then is shown by the curve to which I have referred.

I believe that when we obtain the results of the census for 1910 we shall see a great increase, and that this particular section of the country will be far ahead of any other in the large amount of power supplied through the electric drive in cotton mills.

D. B. Rushmore: Mr. Milmow's paper is of interest in connection with the statements recently made that this country is passing from the position of an agricultural nation to that of an industrial one. The use of electricity for manufacturing purposes is old, but its rapid extension into all such lines is one of the phenomena of the present time.

In the paper under consideration we have an interesting comparison of the steam plant in a particular mill, and electricity taken from a large system—a comparison which must be made in detail in many different individual cases. In general, it is much more economical for the generation and distribution of electric power to be concentrated in the one large system and for the manufacturing industry to buy such power, rather than to generate it in a small plant of its own.

Mr. Milmow has brought out a large number of interesting points illustrating the advantages of electric drive. Many of these are applicable to other forms of industry, and this will be one of the valuable uses of his paper.

L. T. Robinson: I would inquire if Mr. Milmow will take a moment to explain how the speed curves were taken; that is, what sort of an instrument was employed in taking them, and what the time scale on the curves is? I would also call attention to the value, to all concerned in the industrial application of motors, of just such curves as those, shown on page 387. Perhaps he will carry his investigations further and obtain curves on individual machines. The opportunity is always there to use curve drawing instruments on individual motors to check operating conditions and to know if the motors are being run to their full capacity at all times.

Mr. Milmow: We obtained these curves by means of a tachometer specially constructed by Messrs. Schaeffer & Budenberg, applied to the shaft under test by means of a belt. We checked up all these measurements very closely, and one of our curves, Fig. 6, has been inserted there to show the accuracy of the instrument. We have checked the instrument a number of times to determine its accuracy. The instrument itself is rather expensive and cumbersome, and I do not think it would be feasible to apply it in general to industrial applications.

Mr. Robinson: What is the time scale?

Mr. Milmow: That is given in the paper, and is approximately one-half inch in length of the chart, equals one second. You can see that the wave variations are decidedly instantaneous ones.

A paper presented at the Charlotte meeting of the American Institute of Electrical Engineers, March 30, 1910.

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GAS ENGINES IN CITY RAILWAY AND LIGHTING SERVICE

BY E. D. LATTA, JR.

It is not the object of this paper to present the subject of internal combustion engines from a scientific point of view, or to report on results obtained from tests made under the most favorable conditions with apparatus and facilities only to be found in an experimental laboratory, but to consider the subject under the following heads:

First, to give a description of the apparatus and equipment in a small but thoroughly appointed central station, viz: that of the Charlotte Electric Railway Company, using gas engines for prime movers, and supplying current for street railway purposes, electric lighting, and motors in small units.

Second, to give from the daily operating reports, some figures from which can be formed an idea of the reliability, efficiency, and adaptability of the plant under conditions which are relatively as severe as can well be imposed upon any plant, whether large or small. The extremely variable nature of a railway load and its rapid fluctuations caused by a system of few cars with comparatively large individual requirements, is so directly antagonistic to the fine degree of regulation and the continuity of operation demanded by good lighting service, that the handling of such conditions in a creditable manner should receive due consideration as a factor of no small importance.

Third, to give some data on the subject of producer gas manufacture, which to the engineer versed in the principles of fuel combustion may seem obvious and even crude, but which to operators and those investigating the operation of producer gas plants may be of value, in that it can be acquired only by experience and by tedious reference to the works of many authors on the subject of fuel combustion.

Lastly, to offer a few remarks on the adaptability and advisability of gas engines for certain kinds of work.

The period covered by this paper, viz., twelve months, dates from the first of January, 1909, when the plant had been in operation for about six months, and could be considered as being fairly well under way. Much has been learned during the year just passed, and each day gives new experience for the operators. Therefore, while we feel satisfied and even gratified with the record to date, still we feel it is reasonable to expect an improvement over results of the present year, brought about by eliminating some of the petty troubles which experience has taught how to overcome, and thereby attaining a more uniform efficiency of operation.

Description of the Plant

The engine room equipment consists of two 810-b.h.p. horizontal twin-tandem, double-acting four-stroke cycle gas engines and one 60-h.p. single tandem exciter engine, in general similar to the large engines. The 540-kw., three-phase, 60-cycle, 2300-volt alternators, are direct and rigidly connected to the crank shafts of the main engines, and a 40-kw. direct-current generator is direct connected to the exciter engine. In addition to this apparatus there is an induction motor-driven exciter set of the same capacity as the engine exciter, a 300-kw. and a 500-kw. rotary converter, and the usual switchboard equipment.

The producer apparatus is contained in a building about one hundred feet from the power house, and consists of two 1000-h.p. units of twin generator down-draught producers, having a continuous overload capacity of 50 per cent. Each unit consists of two 9-ft. generators, 16 ft. high, having a fuel space 7 ft. in diameter by 8 ft. high above the grate bars, which are of arched fire-clay tile. The generators are connected at the bottom by openings, lined with fire brick, containing water-cooled gate valves, to an economizer or vertical boiler of 100 h.p. rating. From the top of the boilers a 16-in. pipe leads to the bottom of the wet scrubber and from the top of the wet scrubber to the exhauster, or through a by-pass around the exhauster to the dry scrubber. A 60,000-cu. ft. holder receives the gas from the producers and delivers it to the engines. (See cut of producer on page 494.)

To describe the engine more in detail, the cylinders are 24-in.

bore by 36-in. stroke; the fly-wheels are 16 ft. in diameter and weigh 34,000 lb. The entire engine occupies a floor space of 18 ft. by 44 ft. and together with the alternator weighs 500,000 lb. All parts of the engine that come in contact with the hot gases are water-jacketed, including cylinders, pistons, piston rods, mixing chamber, valves and valve seats, and the exhaust pipe down to the floor level. The jacket water from the various parts of the engine empties from separate pipes into open funnels, which enables the operator to determine at all times the temperature of the different parts of the engine.

The ignition is low tension make-and-break, with two igniters to each end of each cylinder. The ignition current is supplied by one of three batteries of five cells each, and requires about 10 volts. This current passes through a separate kicking coil to each igniter, and a pivoted armature at the end of each coil indicates when the igniter is working properly.

The valves are the poppet type and are actuated by bell-cranks which are lifted by cams on the cam-shafts which are geared to the crank shaft and run at half speed. While there are some mechanical objections to the use of cams on account of difficulty of lubrication, still they are supposed to have a decided advantage over eccentrics, which impart a harmonic motion to the valve. By the use of cams with properly designed contours, quick opening and quick closing of the valves is obtained, and there is a relatively long period during which the valve is wide open.

Intake and exhaust valves are located on top and bottom, respectively, of a compartment bolted to the side of the cylinder which acts as a mixing chamber at one time, and explosion chamber at another part of the cycle.

The governors are of the Jahns type, in which the centrifugal force of the weights revolving in a horizontal plane is resisted by the direct pressure of coiled springs, the weights turning on rollers in a constant oil bath which practically eliminates friction. The governor is driven by a belt from the cam-shaft, and carries no load other than that required to revolve itself. The cut-off valve shaft is driven by bevel gears from the cam-shaft through a hunting gear, which is raised or lowered by the governor, and thus advances or retards the motion of the cut-off shaft with regard to the cam-shaft. The cut-off shaft by means of cams serves all cut-off valves. A cut-off latch hook, engaging the cam of the cut-off shaft, releases the cut-off valve by means of a floating lever connected to the inlet valve and latch which lifts the cut-off valve stem until the latch is disengaged. A dashpot on this valve stem permits the valve to close without jar.

The governing is done with a uniform mixture, the amount of which admitted to each cylinder is controlled by the governor through the agency of the cut-off valve gear. Each cylinder has its own separate mixing chamber and mixing valve which regulates the proportion of gas and air, and a disturbance such as a back-fire does not foul the gas going to other cylinders, this feature is a great advantage when close regulation is desired.

A plunger in the face of the fly-wheel works in and out radially against a coiled spring. In case of excessive speed of the fly-wheel, centrifugal force drives the plunger out beyond its normal position and opens a switch in the igniter circuit, thus shutting down the engine and preventing racing in case of the governor belt breaking or the governor otherwise losing control of the engine. This device is tested at regular intervals by depressing the governor, and is found invariably to operate within five or six revolutions above normal speed.

The problem of piston packing which for many years was one of the greatest difficulties in the way of building double acting engines has been solved in a fairly satisfactory manner by the use of metallic packing contained in packing cases. The packing cases each contain five rings of special cast iron made in segments, with overlapping joints, the segments being held in place against the piston rod by a 3/16-in. garter spring drawn around the circumference. The packing case is bolted to the cylinder head by means of a flange, between which and the cylinder head is a ground joint. About once in three months each packing case is removed and supplied with clean packing. The packing removed is then thoroughly cleaned when convenient and put aside for use at another time. If a high grade cylinder oil is used and the packing is regularly cleaned, the troubles from this source are practically eliminated.

The pistons are about 24 in. long and each has six slots in which are cast iron piston rings. The clearance between rings and slots is 12/1000 in. This clearance should be very carefully determined for different engines, as it depends principally upon the kind of gas used, and the nature of the lubricating oil. If the clearance is too small and the gas is not clean or the oil is inferior, the rings will become carbonized and stick in the slots. On the other hand, if the clearance is too great, a hammering action will take place between the rings and slots, and both will become badly battered in a short time. The joints in the rings are staggered and all joints are made at the bottom of the piston. The clearance between the bottom of the piston and the cylinder wall is very small, 11/1000 in. so as to reduce to a minimum the slippage past the piston.

Three cross-heads, one between the cylinders and one at the outer end of each cylinder, carry all the weight of piston and piston rod, relieving the cylinder walls and maintaining the piston rod in alignment.

The lubrication of the main bearings is accomplished by a flushing system of oil operated by turbine pumps, attached to the engine, which carry the oil from the engine through a filter to an elevated tank whence it returns by gravity.

The cylinders are lubricated by multiple pumps positively driven from the cam-shaft, the plungers of these pumps being so timed as to inject oil on the piston at the end of each power stroke.

Two air tanks each 5 ft. in diameter and 10 ft. long, located in the basement of the engine room, are kept charged with air at 150 lb. pressure for starting the engines. This air is delivered to the engine by two distributing valves driven by the cam-shafts, and so timed that air is admitted to each cylinder at the beginning of its power stroke. The compressed air is supplied by two compound steam pumps controlled by automatic governors, the pumps being located in the producer house.

During the summer months about 15 gallons of water, at an initial temperature of 80 degrees fahr., is required per horse power-hour for cooling, the temperature of discharge being about 120 degrees. During the winter months 10 gallons of water per horse power-hour at 60 degrees is sufficient, and it is discharged at about 100 degrees. The difference in the amount of water required in summer and winter is apparently due to the fact that the heat lost by radiation is much greater in winter. Even in the coldest weather that has been experienced since the plant has been in operation no other heat has been required for heating the building, and the temperature has not been found uncomfortable at any time.

The jacket water after being discharged from the engine flows by gravity to a hot well (see Fig. 1) of the cooling system, from which it is drawn by an electrically driven centrifugal pump of 50,000 gallons per hour capacity, against 15 lb. pressure, and forced through sprays into a basin in the middle of which is a cold well. From the cold well it is taken by a two-stage turbine pump of 15,000 gallons per hour capacity against 30 lb. pressure, and returned to the engine. These pumps are driven by the same motor. As the capacity of the single-stage or hot-well pump is three times as great as that of the cold-well pump it follows that an excess of water is sprayed into the basin over that taken out of the cold well; this excess water overflows and returns to the hot well whence it is again pumped through the

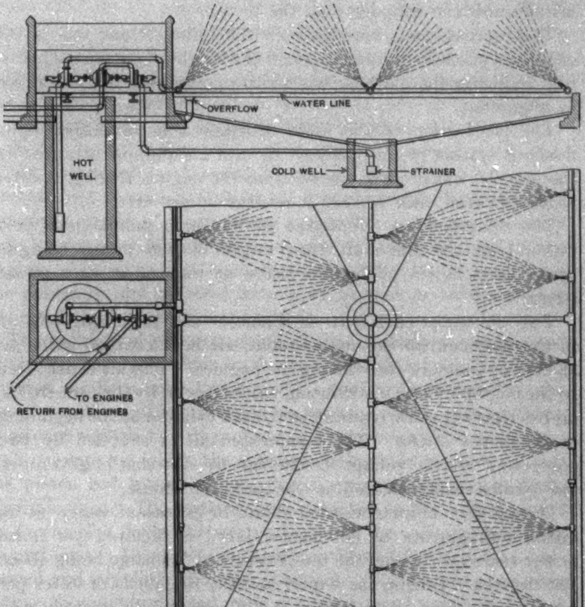

OVERFLOW
WATER LINE
HOT WELL
COLD WELL
STRAINER
TO ENGINES
RETURN FROM ENGINES

FIG. 1—Cooling system for jacket water of gas engine plant

sprays. In this way all the water passes through the sprays three times to each time it is used in the engine and ample cooling is obtained, the water in the cold well is reduced to a temperature slightly below that of the atmosphere. The loss in water by evaporation to attain this degree of cooling is about 10 per cent, although in windy weather there is a slight additional loss occasioned by the blowing away of the spray.

Unlike a steam engine cutting off at 20 per cent to 25 per cent of its stroke for most efficient operation, permitting the steam to expand during the remainder of the stroke, a gas engine's most economical point of operation is attained when a full charge of the gas and air mixture is admitted to the cylinders. This condition is due to the following causes:

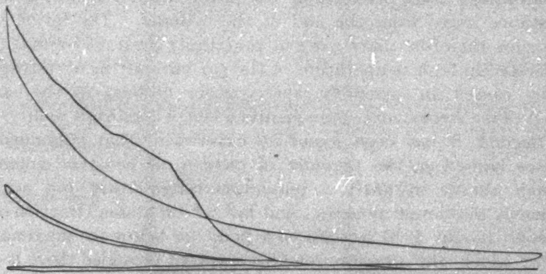
First, the combustion of gas is so rapid, that almost complete combustion takes place before the piston has moved but a little distance away from the end of the cylinder. The initial expansion therefore takes place at practically constant volume, the excessively high temperature of the gas burning in a restricted area causes an extremely rapid transfer of heat in the early part of the stroke, and consequently a loss of expansive ability.

Second, it has been found by experiment that inflammable gases ignited in the presence of oxygen, at constant volume, reach almost instantly a maximum temperature and consequently maximum pressure, and fall within a small fraction of a second (about 1/10 second) to a point far below the maximum, after which the pressure remains constant provided there is no transfer of heat. As one-quarter second is required for the full travel of the piston in one of these engines, it is clear that this rapid decline in pressure takes place before the piston has reached the middle point of its stroke. Both of these conditions largely reduce the expansive work of the gas.

Third, the percentage of inflammable gas contained in a charge of the mixture is small (about 12 per cent), the balance of the charge consisting principally of nitrogen and a small amount of carbonic acid gas, both of which are inert and absorb heat from the combustible constituents. It therefore requires a relatively large intake of the mixture to contain a sufficient amount of active gas to produce a given amount of power.

Under the foregoing conditions it follows that if a gas engine were rated at its most economical load, it would have no overload capacity whatever, but to obviate this condition it is customary to arbitrarily rate a gas engine at 87 per cent of its ultimate continuous capacity, which rating permits of an overload of 15 per cent. In the case of these engines, which are rated at 810 b.h.p. we have frequently carried a load of 700 kw. which is equal to 1010 b.h.p., or nearly 25 per cent overload, for a considerable length of time, and a momentary load of 800 kw. or 42 per cent over load without reducing the speed to a point that caused any trouble. While it would appear from these figures that the engines are somewhat under rated, for continuous operating the 15 per cent overload is as much as should be put upon them. The load of 700 kw., although it does not reduce the speed materially, gradually heats up the engine, with the result that after a few hours operation preignitions occur; also the high pressures in the cylinders strain the packing and cause gas to blow through.

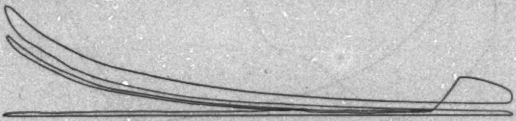
There are three classes of disturbances that take place frequently in these engines, as is the case with all gas engines, viz: preignition, back-fires, and muffler explosions. The first of these is caused by the use of gas over rich in hydrogen, which ignites very readily under high compression without other application of heat; also by particles of carbon or other solid matter which become lodged in the cylinder and become incandescent under the temperature of compression, or when any of the water-cooled parts of the engine are insufficiently cooled by using too little water, or water at too high temperature. Preignition means that the gas becomes ignited during the compression stroke and the burning gas instead of being relieved by the forward motion of the piston as is the case in a power stroke, continues to be compressed until the piston reaches the end of its travel, with the result that back pressure of an extremely high degree is developed



INDICATOR CARD No. 1—Preignition

which momentarily tends to reduce the speed of the engine. Indicator card No. 1, taken at time of preignition, is shown herewith.

A back-fire occurs when the gas admitted to the cylinder is ignited on the suction stroke, but can also be caused by a leaky inlet valve, in which case the gas in the inlet pipe is ignited during the explosion stroke. Ordinarily a back-fire is caused when gas of a too lean nature is used, so that the gas burns very slowly and continues to burn in the exhaust stroke. A part of the gas still burning in the clearance space ignites the incoming charge. Also if there are any pockets or small passages, such as the water-cooled pipe leading to the indicator cock, the gas in the passage or pocket is cooled to a point where it does not ignite readily. It becomes heated and ignites in the latter part of the pressure stroke, and continues to burn until the succeeding intake stroke when the incoming charge is ignited. The result of a back-fire is only the loss of the next power stroke, and usually a mis-fire at the second succeeding power stroke caused by the burning gas blowing back into the intake pipe and fouling the gas contained in it. Back-fires were at first very common with these engines and were caused by a short section of water-cooled pipe leading to the indicator cocks, these pipes were removed, and a different type of indicator cock supplied. In the new type, the valve of the indicator cock seats directly against the outside of the cylinder wall and there is, therefore, no pocket to retain the gas, and back-fires very seldom occur. Indicator card No. 2 shows the result of a back-fire.



INDICATOR CARD No. 2—Back-fire

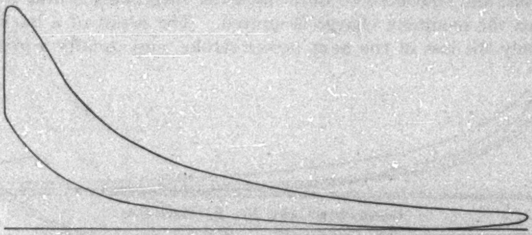
The disturbance caused by preignitions and back-fires is only momentary, and even when the engines are operating in parallel very little effect can be noticed.

A muffler explosion is caused after a mis-fire, when an unburned charge of gas and air passes into the exhaust pipe and is ignited by the exhaust from the power stroke of another cylinder. It has no effect upon the operation of the engine, but makes a noise similar to that of a preignition or back-fire.

Mis-fires seldom occur except following a back-fire as explained above. The double system of ignition practically obviates the possibility of this trouble.

Indicator card No. 3. is a typical gas engine card. It was taken, as were Nos. 1 and 2, with a 150-lb. spring. The compression is 135 lb. and the explosion pressure 267 1/2 lb. The mean effective pressure, as taken with a planimeter, is 53.625 lb. per sq. in., which would develop 311 h.p. per stroke in this one cylinder. As there are two cylinders acting during each stroke, the total indicated horse power of the engine at the moment the card was taken should have been 622 i.h.p. The load observed on the wattmeter at this moment, however, was rising, and was something over 600 kw.

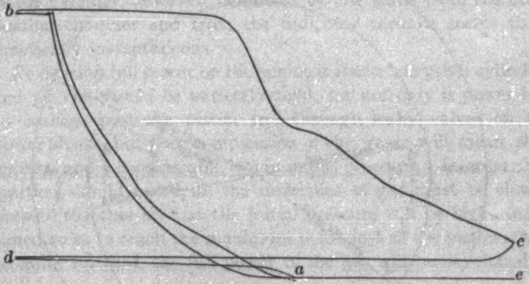
Card No. 4 is taken at light load with a 16-lb. spring; one complete cycle and part of another is shown on the card as follows: *a* to *b* last half of compression stroke, *b* to *c* combustion or power stroke, *c* to *d* exhaust stroke, *d* to *a* to *c* suction stroke, *e* to *a* to *b* compression stroke. At *b* the pencil was lifted. At *a* on the suction stroke the cut-off valve at the inlet closes, and the vacuum increases to a point below the range of the indicator, also at *b* the pressure reaches the other extreme limit of the indicator where it remains until expansion reduces the pressure to a point within the range of the light spring. A card taken with a light spring, as in this case, is of value in that it shows more distinctly than cards taken with a heavier spring the opening of the exhaust valve, and any wear of the cam operating the exhaust valve would be clearly shown by the toe of the card.



Indicator Card No. 3—150-lb. spring; compression 135 lb; explosion pressure 267.5 lb.; mean effective pressure 53.625 lb.

Improper action of a gas engine is not shown nearly as clearly by the indicator card as it is in the case of a steam engine. For instance, the exhaust valve of a gas engine might be leaking and the only indication of the trouble would be low compression, yet the low compression might be caused also by badly worn piston rings or by packing in bad condition. The principal value of the indicator card is in adjusting the proportion of air and gas to give the most effective mixture, and for properly timing the ignition.

To adjust the mixture it is desirable to put a steady load upon the engine, preferably that produced by a water box, and then indicate the engine and adjust the mixing valve until the card shows the maximum explosion pressure for a given compression, which is the condition existing when sufficient air for complete combustion is admitted with the gas, without excess. When once adjusted for gas of a certain quality it is not necessary to change the mixing valve again.



Indicator Card No. 4—16-lb. spring

The indicator is most frequently used for timing the ignition, which can be done with precision in no other way. This becomes necessary at regular intervals on account of wear, both mechanical and electrolytic, of the igniter contacts. From time to time the igniters have to be taken out, cleaned, and the contact points smoothed up, and in replacing the igniter after this overhauling, cards are taken from this cylinder, and the tappet rods which control the make-and-break movement are adjusted so that the card shows proper ignition.

The diagram herewith, Fig. 2, shows the various events of valves and ignition during one cycle, or two revolutions of the fly-wheel. It will be noted that the valves open a number of degrees before the dead center, and close 10 degrees after passing the dead center, while the periods of suction, compression, combustion and exhaust begin and end exactly at the centers. The reason for this apparent discrepancy is that the movement of valves is so very rapid, that a certain time element is required to accommodate the slower movement of the gas. The points indicated as valve openings and valve closings on the diagram, represent the points at which the valves begin to open and are completely closed. As the opening and closing of the valves require an appreciable length of time, the actual period during which the valves are wide open more nearly coincides with the period of travel of the piston. It will be understood that the cut-off valve is released independently of the inlet valve closing, and may occur at any point of the suction stroke, depending upon the load.

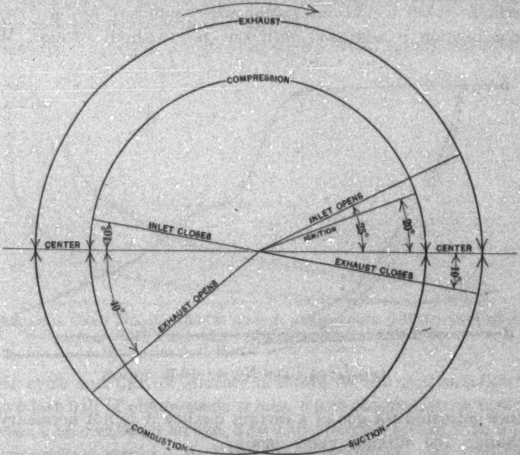


FIG. 2—Valve diagram of four-cycle gas engine

While the ignition is shown to take place at a point 20 degrees ahead of the end of the compression stroke, this location of the ignition is only approximately correct, for, as explained above, the position is located in practice by means of the indicator, and it may vary slightly with the quality of the gas and proportion of mixture. The ignition is timed to occur 20 degrees before reaching the end of the stroke, so that sufficient time will be given for the flame propagation before beginning the power stroke. The ignition of these engines takes place in a combustion chamber just off the end of the cylinder. When the gas in the combustion chamber becomes thoroughly ignited, it bursts out into the clearance space of the cylinder, practically at the time the piston is at the end of its travel, the molecules of gas are compressed to the highest degree, and the flame from the combustion chamber ignites it almost instantly. The flame propagation about the igniters is in spherical form, the surface of the sphere increasing as the square of the time elapsing after ignition. In the combustion chamber, therefore, the time required for the entire volume to become ignited is appreciable. The gas in the cylinder, however, is ignited by the flame from the combustion chamber and from the indicator cards it seems to be practically instantaneous.

To develop full power on the engine it is necessary that cylinders and pistons should be perfectly tight, for not only is power lost by leakage past the piston and through leaky valves on the power stroke, but poor compression of the gases will mean slow ignition and a considerable loss in initial pressure. In order that ignition should be rapid, the molecules of gas must be closely pressed together so that the initial pressure will be high, and if timed so as to reach the maximum point just as the piston starts to move forward, the full power of the gas will be developed.

PLANT PERFORMANCE

Under this head, considering the class of service, we regard reliability as being of paramount importance, and we believe the record, taken from the engineer's daily log, of shut-downs caused by gas and engine troubles only, will be considered extremely creditable when allowance is made for the severe conditions of operation, and the fact that the plant was only in its first full year of existence. Electrical troubles have been decidedly more annoying than engine troubles, but such of these as have no bearing whatever upon the engine or gas operation will not be mentioned inasmuch as they are irrelevant.

From the daily reports we find, as follows:

Jan. 1—Exciter spark plug out of order	5 min.
Jan. 31—Exciter trouble	5 min.
Feb. No trouble.	
Mar. No trouble.	

April 12—Plant shut down caused by suction of engine drawing water from the gasometer over into gas main, causing water trap and shutting off gas supply..45 min.

April 27—Same trouble..30 min.

At the first occurrence it was not known exactly what the source of this water was, and it was attributed to condensation from the gas, but after the second occurrence the trouble was located, and corrected by raising the inner walls of the gasometer, and making the lift necessary to draw the water over the top greater than the suction from the engine could accomplish.

May—No trouble.

June 18—Shut down at one o'clock a.m. caused by belt on oil pump breaking; the other engine was undergoing some slight repairs and was not in condition to start...15 min.

July 23—Shut down on account of igniter wire from battery to engine becoming grounded in conduit. This trouble, although located promptly, could not be repaired without great delay, therefore wire had to be run across engine room floor and old wire cut out..45 min.

July 30—Shut down caused by operation of safety stop on engine, opening igniter circuit..12 min.

Aug.—No trouble.

Sept.—No trouble.

Oct.—No trouble.

Nov.—Shut down caused by unusual overload occurring when only one engine was in operation..8 min.

Dec.—No trouble.

Total interruption of service due to gas and engine troubles........2 hr. 45 min.

In considering these figures it should be borne in mind that the plant operates 24 hours per day and every day in the year.

Other troubles have occurred while both engines were operating, making it necessary to carry the entire load, or the principal part of it, on one engine, but while these occasions caused annoyance, they were handled without serious inconvenience to service.

Second in importance to reliability we regard character of operation, viz: speed regulation, and ability to operate successfully in parallel, the former being a function of the engine only, while the latter involves both engine and alternator.

The manufacturers guarantee as to speed is, that from 25 per cent to full load, the engine will govern within a maximum variation of 2 per cent. This condition is met as regards the mean speed on steady loads. When, however, a heavy load is suddenly thrown on the engine, or removed from it, a momentary swing of not exceeding 2 per cent below or above mean speed for the given load occurs, which is due to overreaching of the governor. While this swing in speed is not excessive, and is found to an equal or even greater extent in high-class reciprocating steam engines, it is rather remarkable that it is not far worse than the above figure in a four-cycle gas engine; for at the moment the load on the engine is changing, the governor has no control whatever upon the charge of gas next to be ignited, since the amount of this charge was regulated in the suction stroke which preceded the compression stroke. For example, assume that the engine is operating at three-quarter load, and the governor by means of the cut-off valves is regulating the amount of gas per charge accordingly; just as one crank reaches dead center and ignition has taken place prior to a power stroke, an additional load is thrown on the engine, making a total load equal to the full capacity of the engine; the cylinder for the next power stroke just ignited is charged with gas for three-quarter load, the cylinder on the other side of the engine is midway of the compression stroke, and is therefore beyond the influence of the governor, and the cylinder on the same side of the engine as the one just ignited is just completing its suction stroke and has been cut off at 75 per cent of the stroke, rendering it, also, out of reach of the governor. We have therefore three impulses of power strokes of three-quarter value before a full load charge of gas can be admitted to the engine, during which time the fly-wheel has turned 270 degrees, and it would be expected that the governor would continue to drop and overreach before corrected by the increased speed from full power strokes. This natural tendency to over-reach on the part of the governor, is reduced to a minimum however by the nice adjustment between the fly-wheel inertia and damping of the governor.

It is generally supposed that the turning moment or angular velocity of a gas engine is uneven and characterized by periodic variations with each impulse, due to the fact that the initial cylinder pressures are extremely high as compared to those of steam engines. This would no doubt be the case with a single-tandem, four-cycle gas engine, but with the twin-tandem engines having four double acting cylinders, eight impulses are given to the fly-wheel in two revolutions or one complete cycle. Therefore, as the cranks of the two sides are quartering, an impulse is imparted to the fly-wheel every 90 degrees, or two impulses per stroke. The impulses thus over-lapping tend to smooth out the variations that otherwise would occur, and permit of a far lighter fly-wheel than could be used with a single-tandem engine. The lighter fly-wheel is less sluggish and consequently promotes good parallel operation, but it is not too light to afford sufficient inertia to practically absorb the variations in crank effort.

We have been convinced of the correctness of this statement by observing the behavior of the alternators at various times when they were running in synchronism, with the engine cranks in almost every possible relation. No difference can be discerned in the action of the switchboard instruments, whether the cranks are in step or in any other possible position.

While the parallel operation of this engine would not be considered good in comparison with steam turbines operating at high speed, with alternators having from two to four field poles, it nevertheless compares favorably with the best type of reciprocating steam engines with alternators having the same number of field poles, viz., sixty, which of course means that the variations in electrical degrees will be thirty times as great per degree of angular variation as would be the case in a turbine of the same capacity, which would operate at 3600 revolutions per minute.

The temperatures of the alternators above room temperatures, so far as can be observed with the constantly varying load, do not indicate an excessive synchronizing current, and there has never been any tendency on the part of the synchronous converters to fall out of step. The smaller converter running from one engine or from both in parallel, shows no signs of hunting, neither does the 500-kw. converter when running from both engines in parallel. It, however, hunts slightly when running on only one engine. This is probably due to the fact that this converter is practically of the same capacity as the one alternator, and the fly-wheel effect of its rotor is too great to permit its conforming to the variations of speed which are greater for a given load with one engine operating alone than when both are in parallel.

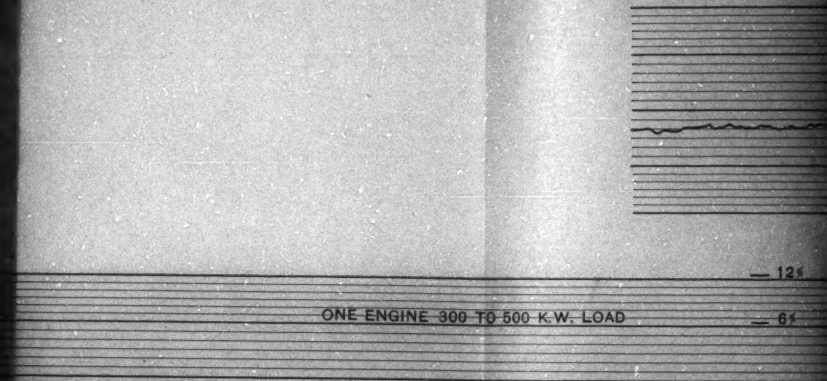
There is a slight periodic swing between the pointers of the wattmeters when the engines are operating in parallel; this is no doubt accentuated by the extreme sensitiveness of the meters, which have 325-degree scales, and by the pendulum motion of the pointers which is common in instruments of this kind. The same swing appears on the ammeters, but to a much less extent. The engines divide the load very equally, and by adjusting the governors they can be made to divide the load in any proportion that may be desired.

Below are shown four speed curves taken with an extremely sensitive graphic recording speed indicator. Each ½ in. of length represents approximately a time interval of one second, and the spaces between lines represent variations of one per cent.

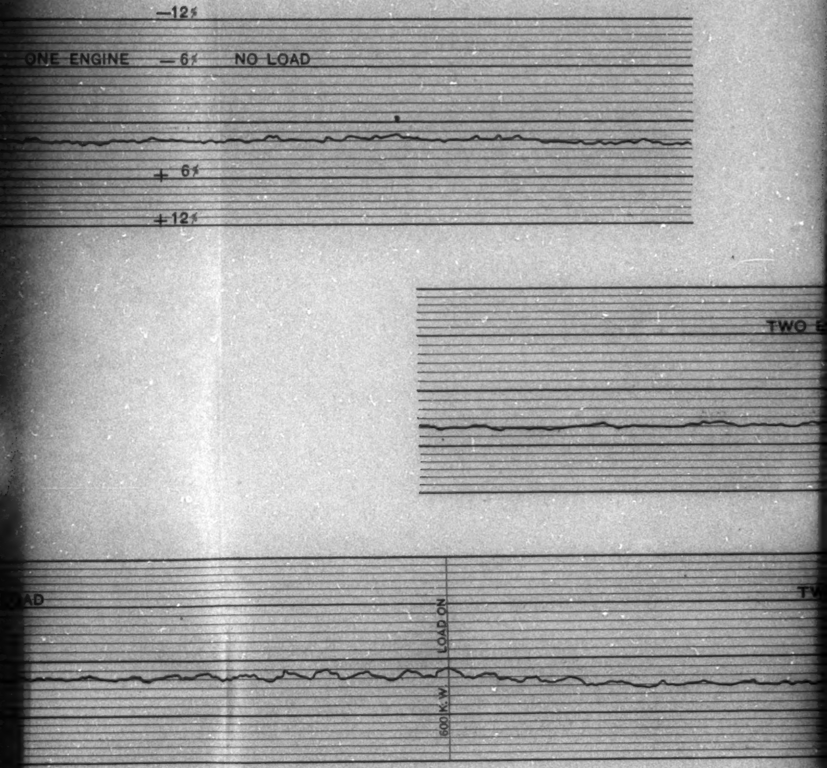
The first record was taken from an engine with no load, and the second was taken from one engine with the load varying from 300 to 500 kw.

The third record was taken from one engine in parallel with the other engine under a total load ranging from 300 to 500 kw.

The fourth record is taken from one of the two engines in



ONE ENGINE 300 TO 500 K.W. LOAD
— 12%
— 6%
+6%
+12%
ENGINES
1100 K.W.
LOAD OFF
600 K.W.
TWO ENGINES 300



howing regulation of gas engines under different loads

parallel, with a load of 300 to 500 kw., and a load of 600 kw. thrown on and off.

COST OF OPERATION AND REPAIRS

The figures given below covering the cost of operation and repairs speak for themselves, and there is little further to be said except to call attention to the extremely low load factor which is the controlling condition. The poor load factor is due principally to two conditions; first, the prevailing load for twenty hours per day is easily within the range of one unit, but the wide limits of variation make it necessary to operate the second engine on an average of ten hours per day; and second, from 12 o'clock night until 6 a.m one engine operates on practically no load at all.

We do not claim high economy for this plant, and can hardly expect it under the circumstances, and while we hope in future to effect a slight reduction in coal consumption by a more consistent and economical operation of the producers, we cannot expect a material improvement in operating cost under the load conditions that obtain.

We estimate that with an increase in the load factor of 25 per cent the additional output could be produced for an amount not exceeding 10 per cent of the present cost, because a higher economy of coal would result from a higher load factor, with practically no increase in labor, water, oil, or other of the larger items that go to make up the total cost.

In the matter of cost of repairs, also, we expect a reduction rather than an increase in the near future. The largest item in the total cost of repair parts is the cost of an entire new equipment of exhaust valves, which amounts to about half of the total. These exhaust valves were put in, not on account of wear and tear, or breakage of the original ones, but on account of their inferior design, which caused them to continually work loose from the stem, which was connected by a flange and studbolts. The new type has proved entirely satisfactory.

Four pistons have been taken out and fitted with new rings, the original rings having become broken when water leaks occurred in the cylinders due to defects in the castings of the piston water compartments. Broken rings almost invariably result from water leaks in a cylinder. In this case, new parts were furnished by the manufacturers without charge, and the labor was furnished principally from the operating force.

Considerable annoyance, though only slight expense, has been occasioned by the backing off of the packing glands around the valve stems, caused by vibration, and a consequent breaking of the exhaust valve casing. This trouble could have been avoided in the beginning, as it has been since, by tapping set screws into the packing glands to prevent their working loose.

The least serious trouble that has been encountered, but one of the most annoying, on account of its occurring at most inopportune times, is the breaking of the wedge adjusting bolts in either the crank or cross head bearings. We have had about six of these break, but the trouble has each time been promptly located, and quickly repaired without further damage resulting.

OPERATING FIGURES

	Engine hours	Kw.-hours	Coal	Coal per kw.-hour	Engine hours	Load factor*
Jan.	1140	304400	570199	1.873	36.8	0.445
Feb.	1060	278800	521190	1.869	37.8	0.438
March	1019	273600	531310	1.942	32.9	0.447
April	1032	256607	501145	1.954	34.4	0.414
May	902	248400	466935	1.879	29.1	0.459
June	872	257300	486804	1.892	29.0	0.492
July	913	275100	528452	1.920	29.5	0.502
August	1111	284900	556959	1.954	36.0	0.427
September	938	276800	533844	1.928	31.3	0.492
October	1102	302000	585037	1.939	35.5	0.457
November	1086	270700	534937	1.975	36.2	0.415
December	1228	327300	627469	1.917	39.6	0.430
Totals	12403	3355907	6444281		34.0 average	0.450 average

$$* \text{Load Factor} = \frac{\text{Output}}{\text{Engine hours} \times \text{capacity of one engine}}$$

In addition to the coal, 260,292 lb. of coke were used in starting producers, of which amount 122,371 lb. were reclaimed, leaving the total net amount used 137,921 lb., equal in cost to 192,000 lb. of coal.

We have, therefore, for the total coal consumption 6,444,281 lb. + 192,000 = 6,636,281 lb.

$$\frac{6{,}636{,}281}{3{,}355{,}907} = 1.97 = \text{lb. of coal per kw-hr.}$$

Assuming 85 per cent efficiency for alternators at 45 per cent load we have

$$\frac{197}{133} \times 85 = 1.275 \text{ lb. of coal per b.h.p-hr.}$$

COST OF CURRENT

Cost of coal per kw-hr	0.349	cts.
Cost of power house labor per kw-hr	0.170	"
Cost of producer labor per kw-hr	0.131	"
Oil for power house	0.065	"
Oil for producer	0.005	"
Waste and sundries, power house	0.012	"
Waste and sundries, producer house	0.003	"
Repair parts for engines	0.046	"
Repair parts for producers	0.007	"
Machine shop work, engines	0.016	"
Machine shop work, producers	0.007	"
Excelsior for producers	0.003	"
Water, both departments	0.071	"
Total cost of current at switch board per kw.-hr	0.885	"

POWER CONSUMED BY AUXILIARIES

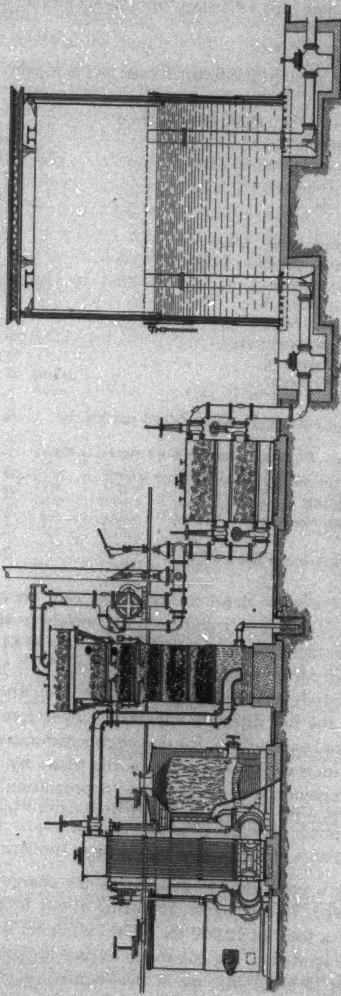
Cooling water pump,	kilowatts	per	kw-hr	0.0095
Station lighting	"	"	"	0.0116
Motor driven exciter	"	"	"	0.0688
Total kilowatts per kw-hr				0.0909

The items of interest, depreciation, taxes, etc., are not included, for the reason that they would be quite unfair to the plant, on account of the fact that it was designed for three 810-h.p. units, while only two have been installed.

Buildings, producers, gas holders, piping, etc., are all installed complete for the full ultimate capacity. Therefore a relatively small additional expenditure for one engine generator and foundation would increase the capacity of the plant by 50 per cent, while the foregoing items of interest, depreciation, etc. would be increased but 18 per cent per unit of capacity installed.

PRODUCER OPERATION

In starting a producer the generators are charged to a depth of five feet with 72-hour coke, requiring about 6000 lb. to each generator, or a total of 12,000 lb. The exhauster is then started, and the coke ignited. The gas made during the first 40 minutes is too inferior to be of any use in the engine, and it is therefore



Gas generating system

blown out through the purge stack and wasted, instead of being admitted to the holder. As the coke in the generators burns and becomes hot, coal is charged at the top in small quantities and at frequent intervals. If coal is charged too rapidly, particularly in the early stages of the fire, it tends to coke, with the result that the draught will be unequally distributed over the fuel bed, finding its way down through holes and localizing the heat to such an extent that the excessive temperature causes clinker to form, thus reducing the capacity of the generator and shortening by several days the time that the set can be run without shutting down for cleaning. When the fuel bed has attained a sufficiently high temperature, the purge stack is closed, and the gas is admitted to the holder. Steam is introduced at the top of the charging doors and, together with the air, is drawn in by the exhauster, passing down through the generator, forming a mixed gas. The carbon of the incandescent fuel combines with the oxygen in the air and steam, forming carbonic oxide gas and free hydrogen, the principal valuable constituents of producer gas.

At intervals of 20 to 30 minutes, up and down steam runs are made in the generators in the following manner: The by-pass around the exhauster is opened, the charging doors of the generators closed, and steam is admitted beneath the grate bars of one generator, the gate valve of which is closed, for about thirty seconds. This steam passes up through the generator, moistens the ash, breaks up the fuel bed and cools the fuel at the point where clinker is forming, and which is not reached by the top steam before decomposition takes place. This steam leaves the generator through a connection at the top, passing over into the top of the second generator, down through the fuel bed and out through the other apparatus to the holder as a fixed gas. The direction of the steam is reversed on the next run, so that the generators are alternately treated in the same manner.

The hot gas leaves the generators at a temperature of about 1200 degrees cent. and passes out through a brick-lined nozzle and water-cooled gate valve into the lower compartment of the vertical economizer, which is also brick-lined. A large part of the sensible heat of the gas is given off and goes to make steam which is used in the generators and for running the exhauster. From the top of the economizer the gas passes, at a reduced temperature, to the bottom of the wet scrubber where it is water sealed, and passing up through the wet scrubber, it works its way through several layers of coke over which water is sprayed from above. During its passage through the coke and water most of the dust and lampblack in the gas is removed, and its temperature is reduced to that of the atmosphere. In the top of the wet scrubber a thick layer of excelsior removes part of the moisture and most of the remaining lampblack. From the wet scrubber the gas goes through the exhauster, then to the dry scrubber, where two more layers of excelsior thoroughly dry it, thence it passes to the holder, a clean, dry, cool gas.

It is very important that the gas should be reduced to atmospheric temperature in the wet scrubber by the use of a sufficient amount of cool water. About four to six gallons per horse power-hour is required, depending upon the temperature of the water and that of the atmosphere. If the gas is allowed to leave the wet scrubber hot, a large amount of water is entrained in the gas and carried in suspension over to the engines. The moisture in the gas is converted into steam by the heat of combustion in the engine, and the latent heat of the steam is absorbed from the burning gas, causing a total loss of this amount of heat to the engine, since the products of combustion are exhausted at a temperature far above that of condensation.

The use of a large holder, such as the one installed in this plant (60,000 cu. ft.) is of great value in operation. It takes up the variations in load and allows the producer to be operated at an even rate; also, if the gas varies in quality over short intervals, which is unavoidable, the gases above and below the mean value are thoroughly mixed and a gas of uniform quality is supplied to the engines.

A strip of metal on one of the guides of the holder, and insulated from it, is divided into ten parts, each representing about two feet lift of the holder. Each section is connected to one of ten lamps arranged vertically on the charging floor of the producer house. A roller on the lift of the holder makes contact with these strips, and lights a lamp in the producer house corresponding to the height of the lift. By means of this tell-tale the output of the producer is regulated. If the holder begins to fall, due to a continued heavy demand by the engines, the speed of the exhauster is increased, and the charging of coal is varied accordingly.

It may be of interest to describe here a rather serious difficulty which was encountered in this plant, and the way in which it was remedied.

A short time after the plant was put into operation, it was found that some of the tubes of the economizers were leaking. The tubes were rolled and the leaks stopped, but in a short time they were found to be leaking again. They were again rolled, but continued to leak, and when finally too thin to be any longer rolled they were taken out and replaced with new tubes. The old tubes when taken out were cut into sections and split open, and it was found that they were badly pitted throughout their entire length, although the pitting was worse at the upper end; weighing the tubes disclosed the fact that they had lost nearly 25 per cent of their original weight. After much surmising, the cause of the pitting of these tubes is believed to be as follows:

In the usual design of plants of this kind, with two or more sets of apparatus, the various sets are absolutely independent of each other as far as the wet scrubbers, and as the gas is water-sealed in the wet scrubbers it is impossible for gas from one set to pass over into another. In this plant, however, in order to increase the flexibility of operation, the two economizers were connected together at the top by a horizontal header, and each one was cut off from the header by a gate valve. These gate valves coming in contact with gas at fairly high temperature expand and contract, and cannot be kept perfectly tight. During steam runs, when the generators were under pressure, leakage of these valves permitted hot gas to pass from the economizer in operation to the one shut down, and after passing down through this economizer to escape through the open generators. It was found that the economizer not in use sweated profusely on account of the difference in temperature of the room and the water in the economizer, keeping the tubes continually wet. This moisture, combining with the hot gas leaking through the apparatus, undoubtedly formed a strong acid and attacked the tubes. Since arriving at this conclusion, each time a producer is shut down the gates of the valves are thoroughly cleaned, the tubes are cleaned with a wire brush, the tube ends and tube sheet are painted with one coat of graphite paint, and the manholes at top and bottom of the economizers are left open, so that a circulation of air prevents sweating. Since adopting these measures, there have been no more leaky tubes, and it is believed that the trouble has been effectually remedied.

At another time an annoying occurrence was the development of numerous hot spots on the shells of the generators; these hot spots were caused by defects in the linings. The brick of the linings were laid with fire clay mortar joints, and the space between brick and shell was grouted with fire clay grout. The jarring occasioned by the heavy barring necessary to remove clinker, broke the bond of the joints and the grout behind the brick becoming pulverized, sifted out when the cleaning doors were open. To correct this trouble holes were tapped in the shell, and fire clay grout forced in at various places under about twenty pounds pressure. As the brick of the linings had thoroughly settled when this was done, no further recurrence of the trouble has been experienced. Had the brick been dipped in fire clay grout and laid brick to brick, and the space between the brick and shell been rammed with a mixture of fire clay grout and shredded asbestos, as is the practice with other gas generating apparatus, the trouble would probably not have occurred.

It is found to be an advantage after cleaning a generator to wash the surface of the brick exposed to the fuel with fire clay grout, as the grout tends to form a cleavage plane between clinker and brick and greatly facilitates its removal. When cleaning the generators, it is not desirable to remove all the clinker, for in doing so a part of the brick would be chipped off each time, and greatly reduce the life of the lining. About one or two inches of clinker adhering to the brick is allowed to remain, and this coating affords great protection to the surface of the lining.

THEORY OF PRODUCER GAS MANUFACTURE AND COMBUSTION

The chemical reactions that take place in the producer generators are practically as follows:

Air passing down over the green coal as it becomes heated by the incandescent coke in the generator, supplies oxygen for combustion of the carbon, and the intense heat produced drives off first the hydrocarbons, which are extremely volatile, in the form of vapor which when condensed becomes tar. This tarry vapor is drawn down through the hot fuel, and most of it burned to lampblack, which is later removed by the wet scrubbers, and the tar, which is most objectionable, is disposed of in a very simple and satisfactory manner. The remaining hydrocarbons are retained as fixed gases in the form of marsh gas or methane, CH_4 and olefiant gas, C_2H_4. These gases are both high in heat value and are extremely valuable, but are obtainable in very small quantities.

The fixed carbon of the coal combines with oxygen from the air or steam admitted, and forms carbonic oxide, CO, and carbonic acid gas. The former, considering the quantity in which it is obtainable, is a most desirable gas; the latter contains no heat and is of no value whatever.

There are two ways in which carbonic oxide gas may be formed. When carbon is burned in oxygen present in insufficient quantity to afford complete combustion, a permanent gas is formed which passes out of the apparatus without further reaction. Since this is a simple and direct process, it would seem most natural and probable that the carbonic oxide is formed in this way. As a matter of fact, however, it has been pretty well established that the principal part if not all of the carbon monoxide gas is formed by a double reaction in the following manner: The air and steam supplied to the producer affords ample oxygen for complete combustion of the carbon in the coal at or near the surface of the fuel. As the complete combustion of carbon gives off heat at the rate of 14,647 B.t.u. per pound, the heat liberated raises the carbonic acid gas (CO_2) formed, to an intensely high temperature, and the hot gas passing down through the already incandescent fuel raises its temperature still higher, driving off carbon vapor, with each volume of which, one volume of carbonic acid gas combines to form two volumes of carbon monoxide. The combination absorbs the same amount of heat that would be given off if an equal weight of carbon monoxide were burned to form carbonic acid gas, *viz.*, 4,383 B.t.u. per pound. Since the molecular weight of carbon is 12 and that of oxygen 16, the product of combustion of one pound of carbon is 3⅔ lb. of CO_2. In the second reaction, the 3⅔ lb. of CO_2 combines with one pound of carbon, making 4⅔ lb. of carbon monoxide (CO) of which 2 lb. consists of carbon and 2⅔ lb. of oxygen. From the pound of carbon burned to form 3⅔ lb. of CO_2 there was liberated and given to the producer 14,647 B.t.u., and in the reduction of 3⅔ lb. of CO_2 to 4⅔ lb. of CO an amount of heat equal to 2⅓ × 4383 = 10,227 B.t.u. per each pound of carbon burned was absorbed from the producer, leaving a net gain to the producer of 4,420 B.t.u. per pound of carbon converted into carbon oxide. This is exactly the same as if a pound of carbon was burned directly to carbon monoxide.

If there was air alone admitted to the producer it can be readily seen that there would be a continual gain in heat to the generator with each pound of coal fired, and while high heat is conducive to a large production of carbon monoxide gas, and is desirable, an excessive heat will fuse the impurities of the coal and form clinker, closing the gas passages through the producer, increasing the vacuum for a given output, and reducing its capacity to such an extent that it becomes necessary to shut it down and remove the clinker. While the production of a certain amount of clinker is unavoidable, the cleaning of a producer entails loss of fuel and expense of labor, and should be postponed as long as possible.

It therefore becomes necessary to control the temperature of the fire, and this constitutes a fine point in producer operation, for only experience can guide the operator, and for the best results good judgment is absolutely necessary.

To cool the fire, steam is admitted at the charging doors together with the air, in an amount depending upon load conditions. First of all, the temperature of the fire must be kept below that which would cause rapid fusing of the impurities. If the design of the engine is such that it will utilize a gas rich in hydrogen, without preignition, the steam may be increased to a point that will reduce the production of carbon monoxide, and increase the carbonic acid, while the loss in heat by the production of carbonic acid gas will be more than compensated for by the high heat value of the hydrogen. The amount of steam cannot be increased indefinitely even if the engines would permit it, for the action of an excess of steam on the fire will cool the fire to such a degree that instead of being decomposed, it will pass through the generator in the form of live steam which is condensed in the holder and carried to the engine in the form of entrained moisture, the effect of which has already been explained. In general, we may say that the amount of steam to be used depends upon the rate of combustion, that is, it must be in proportion to the load, and the proportion depends upon the amount of hydrogen that the engine utilizes without preignition.

The effect of steam upon the fire is as follows: Steam entering at the charging doors and coming in contact with the hot fuel is disassociated into its constituent parts, *viz.*, oxygen and hydrogen. The action of the oxygen from the steam is identical with that of the oxygen in the air, and by combination with the carbon produces heat. Since hydrogen burning in oxygen to form water liberates heat in the amount of 62,032 B.t.u. per pound, conversely, when hydrogen is disassociated from oxygen, an absorption of heat in the same amount takes place. However, as the hydrogen and oxygen are introduced into the generator in the form of steam and as one pound of hydrogen combines with 8 pounds of oxygen to form 9 pounds of steam the latent heat of which from 70 degrees is 1,064 B.t.u. per pound, the net heat absorbed from the producer is $62{,}032 - 9 \times 1064 = 52{,}456$ B.t.u. per each pound of hydrogen liberated,—hence the cooling action of steam.

To demonstrate this effect by figures, the molecular weight of carbon is 12, that of oxygen 16, and that of hydrogen 1. Six pounds of carbon, therefore, will combine with eight pounds of oxygen to form 14 pounds of carbon monoxide, from which the heat evolved is $6 \times 4420 = 26{,}520$ B.t.u., and one pound of hydrogen will be liberated, absorbing 52,456 B.t.u. The loss of heat, therefore, to the generator will be $52{,}456 - 26{,}520 = 25{,}936$ B.t.u. for each 9 pounds, or $\frac{25{,}936}{9} = 2{,}882$ B.t.u. per pound of steam supplied.

Hydrogen gas is very valuable within the limits that permit its use, and it is inexpensive to manufacture. The amount of water required is negligible, and the heat required to convert the water into steam is taken from the gas after leaving the generator, and if not utilized in the economizer would be wasted in the scrubber. Its heat of combustion is very high, and although this heat is borrowed from the generator, it is heat that is liberated in the production of carbon monoxide, and like the heat of the gas, if not absorbed by the hydrogen it would finally be wasted by radiation and in heating the water of the scrubber.

In order that the operator may efficiently perform the duties of his position it is necessary that he should have a clear idea as to the nature and extent of the various losses that occur from the coal pile to the switchboard. For this purpose, actual figures, though not necessarily more than approximately correct, afford the best demonstration.

Taking for example the coal which has been used throughout the operation of this plant, a high grade of Pocahontas coal, we obtain from the United States Geological Survey the following analysis:

Proximate analysis	Per cent	Final analysis	Per cent
Moisture	1.90	Carbon	85.87
Volatile carbon	18.08	Hydrogen	4.65
Fixed carbon	77.03	Oxygen	4.64
Sulphur	0.67	Nitrogen	1.19
Phosphorus	0.008	Sulphur	0.67
Ash	2.312	Phosphorus	0.008
		Ash	2.972
Total	100.0		100.0

Heat value, calculated, 15,039 B.t.u.
Heat value, by calorimeter, 15,344 B.t.u.
This calculated value is checked approximately as follows:

Carbon	85.87 × 14647 = 12577	B.t.u.
Hydrogen	4.65 × 62032 = 2884	"
Total	15461	"
Deducting latent heat of evap. 0.0465 × 9 × 1064 =	445	"
Net heat value	15016	"

At the end of a run on one producer covering a period of 19 days during which time 293,000 lb. of coal was converted, the residual removed in cleaning the generators was carefully weighed, and found to be as follows:

Clinker from generators	13328	lb.
Ashes and lampblack from generators	3221	"
Ashes and lampblack from economizers	168	"
Total	16717	"

and in addition 5,351 lb. of good coke, suitable for use again. The 16,717 lb. of waste material is 5.7 per cent of the total coal converted, and while the analysis of the coal shows only about 3 per cent of sulphur, phosphorus and ash, the balance of weight, *viz.*, 2.7 per cent is no doubt supplied by oxygen with which some of these impurities combine at the high temperature of fusion.

From this coal we assume the gas to have the following analysis by volume, *viz.*

Carbon monoxide CO	20.3
Hydrogen H	11.6
Methane CH_4	1.2
Olefiant Gas C_2H_4	0.3
Carbonic acid CO_2	8.2
Nitrogen N	58.4
Total	100.0

While this is by no means a high grade gas from the above coal, the analysis is assumed purely for the sake of explanation, although it is believed to be a fair average of the gas produced in the plant.

From the above analysis of gas is computed the following table:

TABLE OF GAS AND AIR FOR COMPLETE COMBUSTION

Symbol gas constituent	Per cent by vol.	Weight in one cu. ft. of gas	Per cent by weight	B.t.u. per cu. ft.	B.t.u. one cu. ft. gas	Air in pounds for complete combustion			Products of combustion		Dilutant Nitrogen	Carbon and hydrogen	
						Oxygen	Air	Nitrogen	Pounds CO_2	Pounds H_2O		C pounds	H pounds
CO	20.3	0.015868	21.67	343	69	0.009068	0.039430	0.030362	0.024936	—	—	0.006800	—
H	11.6	0.000648	0.89	347	40	0.005184	0.022540	0.017356	—	0.005832	—	—	0.000648
CH_4	1.2	0.000536	0.73	1072	13	0.001072	0.004661	0.003589	0.001474	—	—	0.000402	—
	—	—	—	—	—	0.001072	0.004661	0.003589	—	0.001206	—	—	0.000134
C_2H_4	0.3	0.000234	0.32	1711	5	0.000534	0.002321	0.001787	0.000734	—	—	0.000201	—
						0.000264	0.001150	0.000886	—	0.000297	—	—	0.000033
CO_2	8.2	0.010122	13.82	—	—	—	—	—	—	—	—	0.002760	—
N	58.4	0.045815	62.57	—	—	—	—	—	—	—	0.045815	—	—
	—	—	—	—	—	—	—	0.057569	—	—	0.057569	—	—
Total......	100.0	0.073223	100.0	—	127	0.017194	0.074763	—	0.027144	0.007335	0.103384	0.010163	0.000815

Air required per cu. ft. of gas for perfect mixture 0.9259 cu. ft.
Air required per pound of gas for perfect mixture 1.0213 pounds.
B.t.u. lost by latent heat of evaporation 0.007335 × 1064 = 7.80 B.t.u. per cu. ft. of gas.
Net heat value of gas 127.0 − 7.80 = 119.2 B.t.u.

Assuming that 72,710 cu. ft. of the above gas will be required by one 810 b.h.p. engine operating for one hour at full load, we then have:

Constituents of gas	Weight in 1 cu. ft.		Weight in 72710 cu. ft.		Heat units	
	C.	H.	C.	H.	Lost in producer	Retained in gas
CO	0.006800		493.55		2,181,491	5,047,535
H		0.000648		47.12		2,922,947
CH_4	0.000402		29.22			427,985
		0.000134		9.74		604,192
C_2H_4	0.000201		14.68			215,018
		0.000032		2.32		143,914
CO_2	0.002760		200.67		2,939,213	
N	inert					
Total			738.12	59.18	5,120,704	9,361,591

Dividing the amount of carbon by the percentage contained in the coal we get $\frac{738.12}{85.87} = 859$ lb. of coal required for 72,710 cu. ft. gas.

In this coal there appears 4.65 per cent of hydrogen of which 4.44 per cent is apparently in the form of hydrocarbons, the hydrogen of which undergoes no reaction in the producer. The balance, 0.21 per cent, is in the form of moisture, and will be classed with hydrogen obtained from steam.

Therefore we have $859 \times 0.0444 = 38.14$ lb. of hydrogen in hydrocarbons and $59.18 - 38.14 = 21.04$ lb. of hydrogen derived from steam, the heat value of which $21.04 \times 62.032 = 1,305,153$ B.t.u. is absorbed from the producer and should be deducted from the total amount under head of "heat lost." We have, therefore, for the net results,

Heat lost in producer, 5,120,704 − 1,305,153 = 3,815,551 B.t.u.
Heat retained in gas........................ 9,361,591 "

Total heat of combustion of 859 lb. of coal . . 13,177,142 "

showing a loss of 28.9 per cent in the producer.

It would seem that the analysis of gas assumed is unfair to the producer, for the relatively small amount of hydrogen (less than 0.40 per cent by weight) introduced into the producer in the form of steam, would indicate that the producer was being operated at high temperature, and therefore a large amount of carbon monoxide would be formed and a correspondingly smaller amount of carbonic acid than the quantities given in the analysis, resulting in a gas of higher heat value and a higher degree of efficiency for the producer.

From 859 lb. of coal consumed, 810 b.h.p. for one hour were produced, from which the coal consumption is $\frac{859}{810} = 1.05$ lb. of coal per b.h.p-hr. This is about in line with the 1.275 lb. of coal per b.h.p-hr. at 45 per cent load factor, which was the average consumption of the plant under discussion for the past year.

From the table we find that one cu. ft. of gas requires 0.926 cu. ft. of air for complete combustion, and therefore 72,710 cu. ft. of gas will require $72{,}710 \times 926 = 67{,}402$ cu. ft. of air, making a total mixture of $72{,}710 + 67{,}402 = 140{,}112$ cu. ft.

The displacement of the piston in one power stroke is 9,574.464 cu. in. = 5.54 cu. ft., and as there are 28,800 power strokes per hour, the total displacement per hour is $28{,}800 \times 5.54 = 159{,}952$ cu. ft. If the full load capacity of the engine is 87 per cent of its ultimate capacity, then $159{,}952 \times 0.87 = 139{,}158$ cu. ft. is the full load displacement per hour, and the suction efficiency of the engine would be $\frac{140{,}112}{139{,}158}$ or a trifle over 100 per cent. As this is not possible it is evident, if the figures are correct, that the assumption of 72,710 cu. ft. of gas at 127.0 B.t.u. per cu. ft. is a little more than required to develop 810 b.h.p.-hr. at the full load rating of the engine, provided the engine is properly rated. However, as the error is small, we will continue in the original assumption as to quantity and value of gas and derive from the above figures the following approximate heat balance:

Heat lost in producer and auxiliaries...........	3,815,551	B.t.u.	28.9	per cent
Heat lost in engine friction at 84 per cent mechanical efficiency $\frac{1980000 \times 154}{772}$............	394,977	"	2.9	"
67437 lb. of water raised 40 degrees, specific heat 1.013:$67437 \times 40 \times 1.013 =$.................	2,734,000	"	20.8	"
Latent heat of evaporation 532.62 lb. steam at 1064 B.t.u. per pound......................	566,707	"	4.3	"
Lost in radiation and exhaust..................	3,588,446	"	27.3	"
Total losses..........................	11,099,681	"	84.2	"
Heat effective in engine $\frac{1980000 \times 810}{772}$.........	2,077,461	"	15.8	"
Total heat of combustion......................	13,177,142	"	100.0	"

Since the specific heat of the products of combustion is not known for temperatures as high as exist in the exhaust, it is impossible to compute the heat lost in this direction, and therefore the heat lost by radiation and by exhaust can only be arrived at by elimination.

The specific heat of the products of combustion containing 15 per cent CO_2 is given as 0.323 for 100 degrees fahr., and it is known that the specific heat of all gases increases considerably with increased temperatures. If the amount of heat, *viz.*, 3,588,446 B.t.u. as derived by our heat balance is correct and the temperature of exhaust 800 degrees above atmospheric, which is approximately true, there being $72710 \times 0.148,123 =$ 10,761 lb. of gas delivered from the exhaust, the specific heat (neglecting loss by radiation of engine) would have to be $\frac{3588446}{10761 \times 800} = 0.413$, as compared to water, which would seem to be a reasonable value.

In Conclusion. That the gas engine has a wide field of usefulness is no longer disputed, but whether it is adapted to conditions of operation such as are met in the plant described is very questionable, unless it be in connection with a storage battery. Other factors however than the conditions of load, as in this case, often enter into the question, and bring influence to bear upon the adoption of a system seemingly unsuitable for the conditions in hand.

The economy of the gas engine has long been conceded, and its reliability at the present time has been proved without a shadow of doubt. An engine in the Edgar Thompson Works of the U. S. Steel Corporation has operated continuously night and day for six months with the total loss of only three hours time; and other records that would do credit to any class of prime mover are to be had in numbers.

When a source of power at low price but uncertain continuity is available, a gas engine and producer will prove a most perfect relay, provided the character of service will warrant the cost of reserve power.

With the holder full of gas and the exhauster of the producer stopped, the fires in the generators will smoulder with almost inappreciable stand-by loss. The engine may be started and put under load in less than two minutes, and the producer can be brought up to working condition before the gas in the holder is exhausted.

Again, when natural or blast furnace gas is available, or when location renders the cost of fuel high, the gas engine has no competitor. Fuel can be utilized in the producer that is absolutely unfit to be burned under a boiler, but even where conditions are more favorable to steam, the gas engine makes a most respectable showing.

DISCUSSION ON "GAS ENGINES IN CITY RAILWAY AND LIGHTING SERVICE", CHARLOTTE, N. C., MARCH 30, 1910.

H. K. English: I have been greatly interested in Mr. Latta's paper on Gas Engines. The record given of plant performance showing a total shut-down of but two hours and forty-five minutes for the year is indeed an enviable one. Also, I consider the data given on operating costs of particular value, as it bears the stamp of "real life" instead of being an engineering estimate, which at best is often only a "wise guess".

It is to be regretted, however, that the items of interest and depreciation have been omitted. Figures on cost of generating power, with these items omitted, are very misleading, this being particularly true of a gas engine plant where installation costs vary widely and little is known regarding such costs. If Mr. Latta would give some figures on installation costs of the plant under consideration, it would add greatly to the value of the other data given.

I would also like to ask Mr. Latta how often he finds it necessary to shut down his gas generators for cleaning, and how long a generator is out of service during this cleaning process.

F. D. Gatchell: Referring to the paragraph of this paper dealing with the piston rod packing, I would like to state that while it is true that the piston rod packings are removed occasionally to be cleaned and adjusted, this is becoming more and more infrequent owing to a better knowledge of how to adjust and assemble this packing before placing it on the piston rod and also to a much better system of lubrication. When these engines were first placed in operation considerable trouble was experienced by the blowing out and leaking of the packing, and if this condition was allowed to go on for any length of time the garter springs holding the segments in place were soon distorted owing to the high temperature of the gas blowing through. This made the packing segments warp and not fit the rod properly. We have overcome these troubles very effectively, however, first, by careful study of the lubricating conditions, and second, by a different method of applying the garter springs. After a series of experiments with different kinds and quantities of oil, we believe that we have hit upon a combination which effectively fits this practice. This is borne out by the fact that we have several sets of packing on these engines which have been in continuous operation for several months, one set having been in service for over ten months without cleaning. This is very desirable for these engines as there are eight sets of piston rod packing on each engine to be kept up.

The method we have adopted in regard to installation of the garter springs which hold the segments of packing together, is that instead of using the continuous spring all the way around the packing as formerly, to divide the spring into short sections connected together with links of solid wire. Each piece of spring takes care of one segment of packing and the joints are bridged by the solid wire. It can readily be seen that as the packing nearly always begins to blow at the joints between the segments, these solid pieces of wire will not be affected by the heat as readily as the springs, and do not stretch, allowing the packing segments to get out of place. We are confident that this simple method of installing these springs has reduced our packing trouble considerably and from indications in the operation of this packing, as used now, it should run several months without adjusting or cleaning.

Referring to the paragraph on page 444 which states that there is a slight periodic swing between the pointers of the wattmeters; it may be of interest to state that since this paper has been written we have discovered that one of the wattmeters was improperly connected and after removing this trouble the so-called periodic swing has been reduced to a marked degree, so that it is hardly perceptible, which would indicate that the fluctuation was principally an instrument trouble rather than one caused by cross currents between the alternators running in parallel.

E. D. Latta, Jr.: If I may be permitted to add a few remarks by way of discussion of my own paper, I should like to call attention to recent experiments made at the University of Illinois on the subject of the occluded gases in coal. These experiments show that when coal is freshly mined a considerable amount of gas exudes from it and simultaneously an absorption of oxygen from the air takes place. The gas escapes rapidly from the coal when first exposed to air, but the rate of escape gradually decreases until at the end of about two months it has practically ceased. Similarly the absorption of oxygen decreases with the time of exposure but to a much less degree, for the experiments indicated that after two years exposure the coal still showed a marked avidity for oxygen, and it is probable that this condition continues indefinitely.

This slow oxidation of coal may account in part for the difference between railroad weights and the weights of coal as fired, for nearly all consumers of coal who carry a large stock on hand, find it necessary to add a certain percentage to the weights of coal as fired in order to balance with the railroad weights.

The gas which escapes from the coal, when freshly mined, consists largely of hydrocarbons in the form of marsh gas, CH_4 which is well known to be the cause of nearly all coal mine disasters. If the analysis of the coal referred to in this paper were made, or samples taken within two months after the coal was mined, it is probable that a subsequent loss of hydrogen in the form of marsh gas occurred, and that the coal as fired did not contain the heat units that the analysis showed. Assuming a possible loss to the coal of 2 per cent of hydrogen subsequent to the analysis, the total higher heat value of the coal per pound would be 14,220 B.t.u. which is more nearly the commercially accepted value of good bituminous coal. The engine efficiency would then become 17 per cent instead of 15.8 per cent and the loss of heat attributed to the producer would be materially reduced, for instead of obtaining 4.44 per cent of hydrogen from the hydrocarbons in the coal, there would be found only 2.44 per cent or 20.95 lb. of hydrogen from 859 lb. of coal. The balance of 38.22 lb. of hydrogen would therefore have to be supplied by the introduction of 344 lb. of steam, in the disassociation of which there would be 2,370,863 B.t.u. absorbed from the producer, reducing the total heat units lost in the producer to 5,120,704 —2,370,869 = 2,749,841 B.t.u., or 20.7 per cent. This figure would show for the producer about the efficiency that is claimed for it by its manufacturers.

A paper presented at the Charlotte meeting of the American Institute of Electrical Engineers, March 30, 1910.

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ON THE MODIFICATIONS IN HERING'S LAWS OF FURNACE ELECTRODES INTRODUCED BY INCLUDING VARIATIONS IN ELECTRIC AND THERMAL RESISTIVITY

BY A. E. KENNELLY

At the meeting of the American Electrochemical Society in October 1909, a paper was read by Mr. Carl Hering on " Laws of Electrode Losses in Electric Furnaces ". At least seven interesting and important laws of electrode losses were enunciated and demonstrated in that paper, of which, however, only the two following need here be considered:

a. The combined loss through the cold end of an electrode is equivalent to the sum of the loss by heat conduction alone, (when there is no current) and half the $I^2 R$ loss.

b. This combined loss will be least when the loss by heat conduction alone is made equal to half the $I^2 R$ loss; the total loss will then be equal to the $I^2 R$ loss, and no heat will be conducted from the interior of the furnace.

In the discussion upon the paper the question was raised as to how far the temperature variation in electric and thermal resistivities of the electrodes modified these laws, since these resistivities might be considerably different at the hot and cold ends. This paper is devoted to a consideration of that question from an arithmetical point of view.

We will assume that both the electric and thermal resistivities are known at the hot end, as well as at the cold end of the electrode, from physical data for the electrode material at the furnace temperature and at the external air temperature. We will also assume that both resistivities change uniformly according to a straight-line law from the known value at the cold end to the known value at the hot end. Thus, in Fig. 1, $O X$ represents the length of an electrode, whose cold end O has a certain resistivity—either electric or thermal—represented by the ordinate $O A$, and whose hot end X has a corresponding resistivity represented to the same scale by the ordinate $X B$. We now assume that at any point P along the electrode, the resistivity considered has a value $P Q$, the point Q being found on the straight line $A B$. This assumption would be entirely justified if the resistivity followed the temperature according to a straight-line law, and also if the temperature increased uniformly along the electrode when at work. But in the working condition, the gradient of temperature is greater near the cold end than near the hot end. If only on this account, the actual resistivity curve probably deviates to one side or the other of the straight line $A B$. In assuming, therefore, straight-line laws of resistivities from one end of the electrode to the other, we arrive at only a first approximation to the true solution of the problem, although we greatly simplify the solution. Nevertheless, the first-approximation solution which we shall develop is probably sufficiently close for ordinary practical purposes, especially as our data concerning the temperature variation of the resistivities is still very meagre. Moreover, since the results indicate that the first-approximation effect of the change in resistivities is relatively small, the necessity for seeking a second approximation becomes yet smaller.

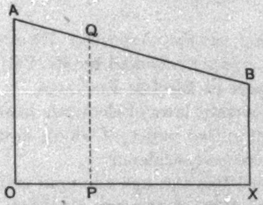

FIG. 1.—Diagram representing the assumed type of straight-line law in linear resistivities

In Fig. 2, $O X$ represents a prismatic electrode with a length $O X$ of X cm., and a uniform cross-sectional area of s cm^2, commencing at the cold end O, the temperature of which is taken as 0 degrees cent., and terminating at the hot end X, the temperature of which is taken as T degrees cent. The electrode is assumed to be perfectly insulated at the sides, both electrically and thermally, by the surrounding furnace wall. If the temperature of the cold end should differ materially from 0 degrees cent. it suffices to reckon this temperature as 0 degrees and to deduct from the furnace temperature T a corresponding amount, so as to maintain the correct difference of temperature between the ends.

In the following demonstration C. G. S. units are employed throughout.

Let t_x = the temperature at any point of the electrode distant x cm. from O. (degrees cent.)

ϕ_x = The flow of heat through a cross-section of electrode distant x cm. from O, and reckoned as positive when in the direction $O\,X$ (abwatts).

I = the current strength passing through the electrode (absamperes).

$\rho_x = \rho_0\,(1+a\,x)$ = the electric resistivity of the electrode at a point distant x cm. from O; where ρ_0 is the resistivity at the cold end, and $\rho_0\,(1+a\,X)$ is the resistivity at the hot end (absohm-cm.).

$\sigma_x = \sigma_0\,(1+b\,x)$ = the thermal resistivity of the electrode at a point distant x cm. from O; where σ_0 is the resistivity at the cold end, and $\sigma_0\,(1+b\,X)$ is the resistivity at the hot end. (thermal absohm-cm.).*

The differential increase in heat flow occurring in the element dx is

$$d\phi_x = I^2\,\frac{\rho_x}{s}\,dx = I^2\,\frac{\rho_0}{s}\,(1+a\,x)\,dx \qquad \text{abwatts (1)}$$

$$\therefore \frac{d\phi_x}{dx} = I^2\,\frac{\rho_0}{s}\,(1+a\,x) \qquad \text{abwatts/cm. (2)}$$

---

* A unit cube of material of thermal resistivity σ absohm-cm. will permit a thermal flow of $1/\sigma$ abwatts, or ergs per second, when a difference of temperature of 1 degree cent. is maintained between a pair of opposite faces. The constants a and b may be either both positive, or both negative, or of opposite signs.

Also

$$\phi_x = -\frac{s}{\sigma_x} \cdot \frac{dt_x}{dx} = -\frac{s}{\sigma_0\,(1+b\,x)} \cdot \frac{dt_x}{dx} \qquad \text{abwatts} \quad (3)$$

where the negative sign indicates that the flow of heat has a direction opposite to the positive direction of temperature gradient.

$$\therefore \frac{d\,t_x}{dx} = -\phi_x \frac{\sigma_0}{s}(1+b\,x) \qquad \text{degrees cent. per cm.} \quad (4)$$

Differentiating with respect to x, we have:

$$\frac{d^2\,t_x}{dx^2} = -\frac{d\phi_x}{dx} \cdot \frac{\sigma_0}{s}(1+b\,x) - \phi_x \frac{\sigma_0}{s} b$$

degrees cent. per cm. per cm (5)

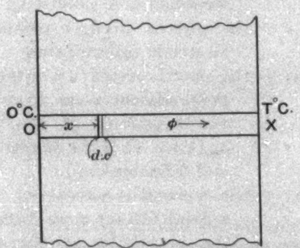

FIG. 2.—Electrode of uniform cross-section insulated both electrically and thermally in furnace wall

Substituting in (5) the value of $\frac{d\phi_x}{dx}$ in (2),

$$\frac{d^2 t_x}{dx^2} = -I^2 \frac{\rho_0\,\sigma_0}{s^2}(1+ax+bx+abx^2) - \phi_x \frac{\sigma_0}{s} b$$

degrees cent. per cm. per cm. (6)

Differentiating again with respect to x,

$$\frac{d^3 t_x}{dx^3} = -I^2 \frac{\rho_0\,\sigma_0}{s^2}(a+b+2abx) - I^2 \frac{\rho_0\,\sigma_0}{s^2}(b+abx)$$

degrees cent. per cm. per cm. per cm. (7)

$$= -I^2 \frac{\rho_0\,\sigma_0}{s^2}\,(a+2b+3abx)$$

degrees cent. per cm. per cm. per cm. (8)

This is the fundamental differential equation connecting temperature with distance along the electrode. Integrating with respect to x, we have:

$$\frac{d^2t_x}{dx^2} = -I^2 \frac{\rho_0\,\sigma_0}{s^2}\left\{(a+2\,b)x+\frac{3ab}{2}\,x^2\right\}+A$$

degrees cent. per cm. per cm. (9)

$$\frac{dt_x}{dx} = -I^2 \frac{\rho_0\,\sigma_0}{s^2}\left\{\left(\frac{a+2\,b}{2}\right)x^2+\frac{a\,b}{2}\,x^3\right\}+Ax+B$$

degrees cent. per cm. (10)

$$t_x = -I^2 \frac{\rho_0\,\sigma_0}{s^2}\left\{\left(\frac{a+2b}{6}\right)x^3+\frac{a\,b}{8}\,x^4\right\}+\frac{A}{2}\,x^2+Bx$$

degrees cent. (11)

where A and B are integration constants to be determined from the terminal conditions. No new integration constant appears in (11) because $t_0 = 0$, by assumption.

In order to determine B, we may substitute X for x in (11), in which case $t_x = T$ degrees cent. This gives:

$$T = -I^2 \frac{\rho_0\,\sigma_0}{s^2}\left\{\left(\frac{a+2b}{6}\right)X^3+\frac{ab}{8}\,X^4\right\}+\frac{A}{2}X^2+BX$$

degrees cent. (12)

from which,

$$B = \frac{T}{X}-\frac{A}{2}\,X+I^2\frac{\rho_0\,\sigma_0}{s^2}\left\{\left(\frac{a+2b}{6}\right)X^2+\frac{a\,b}{8}\,X^3\right\}$$

degrees cent. per cm. (13)

substituting this value of B in (10), we obtain:

$$\frac{dt_x}{dx} = \frac{T}{X}-\frac{A}{2}\,(X-2\,x)+I^2\frac{\rho_0\,\sigma_0}{s^2}\left\{\left(\frac{a+2b}{6}\right)(X^2-3x^2)\right.$$

$$\left.+\frac{ab}{8}\,(X^3-4\,x^3)\right\}$$

degrees cent. per cm. (14)

Using this result in (3), we have:

$$-\phi_x = \frac{1}{1+b\,x}\left[\frac{s}{\sigma_0}\cdot\frac{T}{X}-\frac{As}{2\sigma_0}(X-2\,x)\right.$$

$$\left.+I^2\,\frac{\rho_0}{s}\left\{\left(\frac{a+2\,b}{6}\right)(X^2-3\,x^2)+\frac{a\,b}{8}\;(X^3-4\,x^3)\right\}\right] \quad \text{abwatts (15)}$$

There remains the constant A to be determined from the known conditions of thermal flow. This constant A, which appears in (9) as a rate of change of temperature gradient, may be conveniently expressed as the sum of two parts, or

$$A = A_1 + A_2 \qquad \text{degrees cent. per cm. per cm. (16)}$$

where A_1 depends only on the furnace heat-flow, or the flow of heat which would take place through the electrode in the absence of electric current, and A_2 depends only on the joulean heat-flow, or the flow of heat which would take place in the electrode with the electric current acting, but with no furnace heat, or a temperature 0 degrees cent. at both ends.

The total furnace flow will be obtained by dividing the difference of temperature, or thermomotive force, by the total thermal resistance of the electrode $\mathcal{R}$, which is

$$\mathcal{R} = \int_0^X \frac{\sigma_x}{s}\,dx = \frac{\sigma_0}{s}\int_0^X (1+b\,x)\,dx = \frac{\sigma_0}{s}\,X(1+b\,\frac{X}{2}) \quad \text{thermal absohms (17)}$$

This means that the thermal resistance of the electrode, with a thermal resistivity varying in the manner assumed, is the same as that of an electrode having the same dimensions and a constant resistivity, equal to the arithmetical mean resistivity of the first. The furnace flow is thus:

$$-\phi_{x\,(I=0)} = \frac{Ts}{\sigma_0\,X\;(1+b\mathrm{v})} \qquad \text{abwatts (18)}$$

where $\mathrm{v} = X/2$

Putting $I = 0$ in (15) we obtain:

$$\frac{Ts}{\sigma_0 X(1+b\text{v})} = \frac{Ts}{\sigma_0 X(1+bx)} - \frac{A_1 s(\text{v}-x)}{\sigma_0 (1+bx)} \quad \text{abwatts} \quad (19)$$

from which

$$A_1 = \frac{T}{X}\left(\frac{b}{1+b\text{v}}\right) \quad \text{degrees cent. per cm. per cm.} \quad (20)$$

The total joulean heat flow will be the integral of the $I^2 R$ loss in the electrode. The total electric resistance R is:

$$R = \int_0^X \frac{\rho_x}{s}\,dx = \frac{\rho_0}{s}\int_0^X (1+a\,x)\,dx = \frac{\rho_0}{s} X\left(1+a\frac{X}{2}\right) \quad \text{absohms} \quad (21)$$

That is, the total resistance of the electrode with an electric resistivity varying in the manner assumed, is the same as that of an electrode having the same dimensions, and a constant resistivity equal to the arithmetical mean resistivity of the first. The total joulean flow is then, with $T = 0$:

$$-\phi_0+\phi_X = I^2\frac{\rho_0}{s}X\,(1+a\,\text{v}) \quad \text{abwatts} \quad (22)$$

In (15), first put $T = 0$; $x = 0$; and then $T = 0$, $x = X$.

$$-\phi_0 = -A_2\frac{s\,\text{v}}{\sigma_0} + I^2\frac{\rho_0}{s}\left\{\left(\frac{a+2\,b}{6}\right)X^2 + \frac{a\,b}{8}X^3\right\} \quad \text{abwatts} \quad (23)$$

$$\phi_X = -A_2\frac{s\,\text{v}}{\sigma_0(1+bX)} + \frac{I^2\rho_0}{s(1+bX)}\left\{\left(\frac{a+2\,b}{6}\right)2\,X + \frac{3\,a\,b}{8}X^3\right\} \quad \text{abwatts} \quad (24)$$

Adding (23) to (24) and equating to (22), we obtain:

$$A_2 = \frac{I^2\rho_0\sigma_0}{s^2(1+b\text{v})}\left\{\frac{bX^2(4a+8b+3abX)}{24} - 1\right\} \quad \text{degrees cent. per cm. per cm.} \quad (25)$$

Substituting the above values for A and B in (11) and (15):

$$t_x = \frac{Tx}{X}\left(\frac{2+b\,x}{2+b\,X}\right) + I^2\,\frac{\rho_0\sigma_0 x}{s^3}\left[\left\{\left(\frac{a+2\,b}{6}\right)(X^2)^2x -+ \frac{ab}{8}(X^3-x^3)\right\}\right.$$

$$\left. - \frac{X-x}{2\,(1+b\,\mathrm{v})}\left\{\frac{bX^2\,(4a+8b+3abX)}{24} - 1\right\}\right]$$

degrees cent. (26)

and

$$-\phi_x = \frac{T}{X}\,\frac{s}{\sigma_0}\left(\frac{1}{1+b\mathrm{v}}\right)$$

$$+\frac{I^2\,\rho_0}{s\,(1+b\,x)}\left[\left\{\left(\frac{a+2\,b}{6}\right)(X^2-3\,x^2)+\frac{a\,b}{8}\,(X^3-4\,x^3)\right\}\right.$$

$$\left. -\left(\frac{\mathrm{v}-x}{1+b\mathrm{v}}\right)\left\{\frac{bX^2(4a+8b+3abX)}{24}-1\right\}\right] \qquad \text{abwatts (27)}$$

Consequently, substituting $x = X$ and $x = 0$ successively, we obtain after rearranging the terms:

$$-\phi_X = \frac{T}{X}\,\frac{s}{\sigma_0\,(1+b\,\mathrm{v})} - \frac{I^2\,\rho_0\,\mathrm{v}}{s\,(1+b\,\mathrm{v})}\left\{1+X\left(\frac{2\,a+b}{3}\right)+X^2\frac{a\,b}{4}\right\}$$

abwatts (28)

$$-\phi_0 = \frac{T}{X}\,\frac{s}{\sigma_0\,(1+b\,\mathrm{v})} + \frac{I^2\,\rho_0\,\mathrm{v}}{s\,(1+b\,\mathrm{v})}\left\{1+X\left(\frac{a+2\,b}{3}\right)+X^2\,\frac{a\,b}{4}\right\}$$

abwatts (29)

Equations (26) to (29) contain the complete solution of the problem under the assigned conditions. If we assume constant resistivities, or $a = b = 0$, they become:

$$t_x = T\,\frac{x}{X} + I^2\,\frac{\rho_0\,\sigma_0}{s^2}\,x\left(\frac{X-x}{2}\right) \qquad \text{degrees cent. (30)}$$

$$-\phi_x = \frac{T}{X}\cdot\frac{s}{\sigma_0} + I^2\,\frac{\rho_0}{s}\,(\mathrm{v}-x) \qquad \text{abwatts (31)}$$

$$-\phi_X = \frac{T}{X}\cdot\frac{s}{\sigma_0} - I^2\,\frac{\rho_0\,\mathrm{v}}{s} \qquad \text{abwatts (32)}$$

$$-\phi_0 = \frac{T}{X} \cdot \frac{s}{\sigma_0} + I^2 \frac{\rho_0 \mathrm{v}}{s} \qquad \text{abwatts (33)}$$

which correspond completely to the formulas given in Mr. Hering's paper. That is, the total heat flow at the cold end is the sum of the furnace flow and half the joulean flow.

If we retain a in formulas (26) to (29), but put $b = 0$; *i e*, assume constant thermal resistivity, we obtain:

$$t_x = T\frac{x}{X} + I^2 \frac{\rho_0 \sigma_0}{s^2} x \left\{ \frac{a}{6}(X^2 - x^2) + \frac{X-x}{2} \right\} \qquad \text{degrees cent. (34)}$$

$$-\phi_x = \frac{T}{X}\frac{s}{\sigma_0} + I^2 \frac{\rho_0}{s} \left\{ \frac{a}{6}(X^2 - 3x^2) + (\mathrm{v} - x) \right\} \qquad \text{abwatts (35)}$$

$$-\phi_X = \frac{T}{X}\frac{s}{\sigma_0} - I^2 \frac{\rho_0}{s} \mathrm{v} \left(1 + \frac{2}{3} a X\right) \qquad \text{abwatts (36)}$$

$$-\phi_0 = \frac{T}{X}\frac{s}{\sigma_0} + I^2 \frac{\rho_0}{s} \mathrm{v} \left(1 + \frac{a}{3} X\right) \qquad \text{abwatts (37)}$$

Similarly, if we retain b in formulas (26) to (29), but put $a = 0$; *i.e.*, assume constant electric resistivity, we obtain:

$$t_x = T\frac{x}{X}\left(\frac{2+bx}{2+bX}\right) + I^2 \frac{\rho_0 \sigma_0}{s^2} x \left\{ \frac{b}{3}(X^2 - x^2) - \frac{X-x}{2(1+b\mathrm{v})}\left(\frac{b^2}{3}X^2 - 1\right) \right\} \qquad \text{degrees cent. (38)}$$

$$-\phi_x = \frac{T}{X}\frac{s}{\sigma_0}\left(\frac{1}{1+b\mathrm{v}}\right) + I^2 \frac{\rho_0}{s(1+bx)} \left\{ \frac{b}{3}(X^2 - 3x^2) - \left(\frac{\mathrm{v}-x}{1+b\mathrm{v}}\right)\left(\frac{b^2}{3}X^2 - 1\right) \right\} \qquad \text{abwatts (39)}$$

$$-\phi_X = \frac{T}{X}\frac{s}{\sigma_0(1+b\mathrm{v})} - \frac{I^2 \rho_0 \mathrm{v}}{s(1+b\mathrm{v})}\left(1 + X\frac{b}{3}\right) \qquad \text{abwatts (40)}$$

$$-\phi_0 = \frac{T}{X}\frac{s}{\sigma_0(1+b\mathrm{v})} + \frac{I^2 \rho_0 \mathrm{v}}{s(1+b\mathrm{v})}\left(1 + X\frac{2b}{3}\right) \qquad \text{abwatts (41)}$$

Formulas (36) and (37) show that with the electric resistivity alone varying, the joulean heat does not divide equally between the two ends of the electrode. The part escaping through the furnace end is such as would be produced in an electrode of uniform resistivity equal to that actually found at distance $X/3$ cm. from X; while the part escaping through the external end is such as would be produced in an electrode of uniform resistivity equal to that actually found at distance $X/3$ cm. from O. With a essentially negative in carbon, the joulean flow through the furnace end would be less than that through the external end.

Formulas (28) and (29) may also be obtained in a different way, as follows: Referring to Fig. 2, the joulean power developed in the element dx is defined by equation (1). This power divides into two current elements, one $d\phi_x$ escaping through the furnace end, and the other $-d\phi_0$, escaping through the outer end. This division may be expressed:

$$d\phi = -d\phi_0 + d\phi_X \qquad \text{abwatts (42)}$$

The division is effected in inverse proportion to the thermal resistances on each side of the element dx. The thermal resistance $\mathcal{R}_0$ between O and x is:

$$\mathcal{R}_0 = \frac{\sigma_0}{s}\, x \left(1 + \frac{b}{2}\, x\right) \qquad \text{thermal absohms (43)}$$

The thermal resistance $\mathcal{R}_X$, between x and X is:

$$\mathcal{R}_X = \frac{\sigma_0}{s} \left\{ (X - x) + \frac{b}{2}\, (X^2 - x^2) \right\} \qquad \text{thermal absohms (44)}$$

The total thermal resistance $\mathcal{R} = \mathcal{R}_0 + \mathcal{R}_X$ from O to X is expressed by (17). The divisional currents are therefore:

$$-d\phi_0 = d\phi\, \frac{\mathcal{R}_X}{\mathcal{R}} = d\phi\, \frac{(X - x) + \frac{b}{2}(X^2 - x^2)}{X\,(1 + b\,\mathrm{v})} \qquad \text{abwatts (45)}$$

$$= \frac{I^2 \rho_0 (1 + ax) \left\{ (X - x) + \frac{b}{2}(X^2 - x^2) \right\} dx}{sX\,(1 + b\,\mathrm{v})} \qquad \text{abwatts (46)}$$

$$d\phi_x = d\phi\,\frac{\mathcal{R}_0}{\mathcal{R}} = d\phi\,\frac{x\left(1+\frac{b}{2}x\right)}{X\,(1+b\,\mathrm{v})} \qquad \text{abwatts (47)}$$

$$= \frac{I^2\rho_0(1+ax)\left\{x\left(1+\frac{b}{2}\,x\right)\right\}dx}{sX\,(1+b\mathrm{v})} \qquad \text{abwatts (48)}$$

Integrating (46) and (48) from $x = 0$ to $x = X$, we find the total currents $-\phi_0$ and ϕ_x, as expressed in (28) and (29) respectively, after taking the furnace flow into account as in (18).

NUMERICAL EXAMPLE NO. 1, WITH CONSTANT THERMAL RESISTIVITY, OR $b = 0$

We may take as an example a graphite electrode of length $X = 50$ cms. and of uniform cross-section $s = 100$ sq. cm., terminating in a furnace with a temperature elevation of $T = 1600$ degrees cent. Let us first assume that both the electric and thermal resistivities of this electrode are uniform throughout its length ($a = b = 0$). We may take the electric resistivity as $\rho = 0.85\times 10^6$ absohm-cm.* (0.00085 ohm across a block 1 cm. cube, or 0.000333 ohm across a block 1 inch cube), and the thermal resistivity as $\sigma = 2.5\times 10^{-7}$ thermal absohm-cms. (1 degree cent. across a block 1 cm. cube would transmit $1/(2.5\times 10^{-7})$ abwatts of thermal flow, *i e.*, 1/2.5 watts; or $1/(2.5\times 4.19)$ gm. calories per sec.)

The steady current strength which will be consistent with the minimum waste of heat in this electrode will be, by (33) $I = 245.6$ absamperes (2456 amperes), representing a current density of 24.56 amperes per sq. cm. The electric resistance of the electrode will be 0.425×10^6 absohms (0.425×10^{-3} ohm), the drop of potential in the electrode 1.044×10^8 abvolts (1.044 volts) and the joulean power expended $I^2R = 2.560\times 10^{10}$ abwatts (2560 watts).

The thermal conditions of the electrode are represented in Fig. 3, where abscissas along OX represent distances, and ordinates the temperature to the right-hand scale in degrees cent. The thermal current strength is indicated in watts to the left-hand scale. The straight line OT indicates the temperature at different points along the electrode, in the steady state, when no electric current flows, but the furnace temperature is independently maintained. The parabola OPX indicates the temperature which would be reached, in the steady state, at each point of the electrode, if the furnace were cold but full

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* The thermal and electric resistivities used in this example are borrowed from Mr. Hering's October paper.

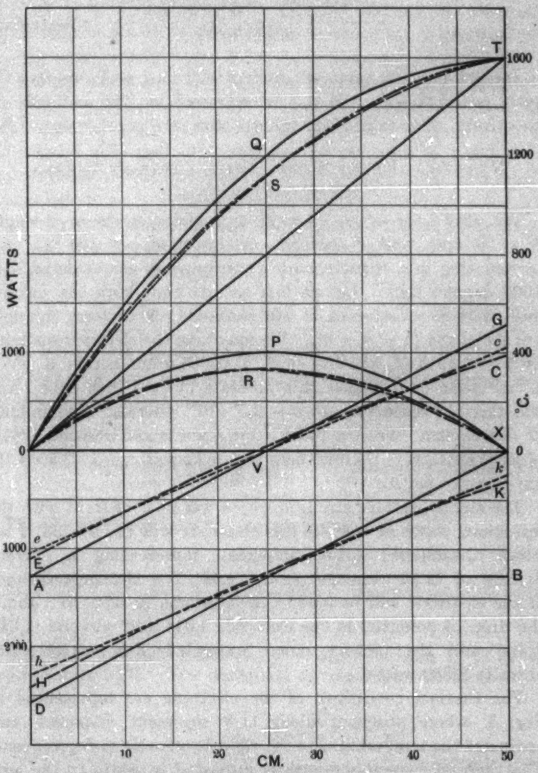

Fig. 3.—Thermal chart for electrode of uniform thermal resistivity

electric current were maintained. Thus, the middle point P of the electrode would attain a temperature elevation of 399.5 degrees cent.; while the two extremities O and X would have no temperature elevation.

Under working conditions the above two thermal states would be superposed, and the temperature at each point of the electrode is shown by the curve $O\,Q\,T$, which is the parabola $O\,P\,X$ superposed on the straight line $O\,T$.

Again, the furnace temperature elevation of 1600 degrees cent. working through the thermal resistance of the electrode (1.25×10^{-7} thermal absohms), would determine a thermal current flow of $1600/1.25\times10^{-7} = 1.28\times10^{10}$ abwatts or 1280 watts, which is constant at all points along the electrode, as indicated by the horizontal straight line $A\,B$. Again with the furnace cold, and the electrode active, there would be no thermal current at the middle point V; but there would be a positive, or furnace-directed thermal current at all points between V and X, together with a negative, or outwardly-directed, thermal current at all points between O and V. This condition is represented by the straight line $A\,V\,G$, with 1280 thermal watts escaping from each end. In the working condition, the above thermal currents are superposed and the total current is represented by the straight line $D\,X$, with no current in either direction at the furnace end, but with 2560 thermal watts leaving the outer end O. All this is in accordance with the principles enunciated in Mr. Hering's paper.

Let us next assume that at the furnace end, owing to the influence of the temperature elevation of 1600 degrees cent., the electric resistivity of the graphite electrode is only 64 per cent of its value at the outer end; or $\rho_X = 0.544\times10^6$ absohm-cm., also that the resistivity falls uniformly from O to X as expressed by the relation $a = -0.0072$, or $\rho_x = 0.85\times10^6\ (1-0.0072\,x)$ absohm-cm. Then if the thermal resistivity remains constant, ($b = 0$) we find by formula (34) that the furnace temperature gradient $O\,T$ Fig. 3 remains unchanged; but the curve of joulean temperature gradient $O\,R\,X$ is no longer a parabola, but a cubic, which reaches its maximum (330 degrees) at R, about 23 cm. from O, the two sides $O\,R$ and $X\,R$ being dissymmetrical. The total temperature gradient in the working state is the broken line $O\,S\,T$, and is the sum of the broken line $O\,R\,X$ and the straight line $O\,T$.

Again, the furnace thermal current through the electrode is shown at $A\,B$, 1280 watts as before; but the joulean current is the broken line $E\,C$, with 973 watts flowing out of the furnace end, and 1127 watts from the outer end. The total thermal current in the working state is indicated by the broken curved line *H K*, with 307 watts escaping from the furnace, and 2407 watts escaping at the outer end.

If instead of using the correction formulas (34) and (35), we assume a constant electric resistivity at the mean value between ρ_0 and ρ_x, or $\rho = 0.697 \times 10^6$ absohm-cm. ($a = b = 0$), then the furnace gradient *O T* remains unchanged; but the joulean gradient becomes a new parabola, represented by the dotted line *O R X*, reaching its maximum of 328.7 degrees cent. at the middle point *V* of the electrode. The total temperature gradient is then the dotted line *O S T*, which differs only very slightly from the broken line *O S T* of the correction formula. Again, the joulean thermal current is indicated by the dotted straight line *e c*, intersecting *O X* in *V*. The flow out of each end of the electrode is 1050 watts. The total thermal current in the working state is indicated by the straight line *h k* with 230 watts escaping from the furnace, and 2330 watts from the outer end.

It is evident that with the electrode dimensions, the range of temperature elevation, and the resistivity here assumed, the corrected formula only changes the thermal current by 77 watts at each end.

NUMERICAL EXAMPLE NO. 2, WITH BOTH RESISTIVITIES VARIABLE

We may next consider a case in which both the electric and thermal resistivities vary. This is represented in Fig. 4. The electrode dimensions, furnace temperature elevation, and electric current strength, are all taken as in the preceding case; but we assume $\rho_x = 0.85 \times 10^6 \, (1 - 0.0072\, x)$ absohm-cm. and $\sigma_x = 2.5 \times 10^{-7} \, (1 + 0.01\, x)$ thermal absohm-cm., which make at the furnace end the electric resistivity 36 per cent less, and the thermal resistivity 50 per cent greater, than their respective values at the outer end *O*. Computing the distribution of temperature and thermal current by the correction-formulas (26) and (27) we obtain the broken lines of Fig. 4. The furnace gradient is *O U T*, no longer a straight line, the drop of thermal potential (temperature) being greater toward the furnace end where the resistivity is greater. The joulean gradient is the broken curve *O R X*, which, being a cubic, is not symmetrical, and which reaches a maximum of 405 degrees cent. about 26 cm. from *O*. The total gradient in the working state is shown at *O S T*.

The furnace thermal current *A B*, Fig. 4, is 1025 watts, uniform at all points, and directed towards *O*. The joulean thermal current is indicated by the broken curved line *E c*, that leaving the furnace at *X* being 910 watts, and that leaving the outer end *O* being 1206 watts. The total thermal current is given by

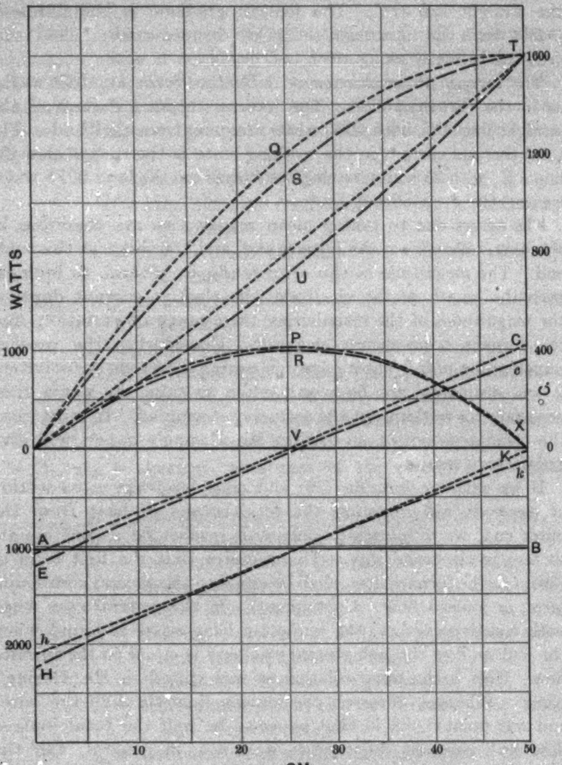

FIG. 4.—Thermal chart for electrode having variation in both electrical and thermal resistivities

the broken line *H k*, 115 watts leaving the furnace at *X*, and 2231 watts leaving the outer end at 0.

If instead of using the correction formulas, we take the simple formulas (30) and (31) of constant resistivities, and the arithmetical mean of each, we have $a = b = 0$, $\rho = 0.697 \times 10^6$ absohm-cm., $\sigma = 3.125 \times 10^7$ thermal absohm-cm. We then obtain the dotted lines of Fig. 4. The furnace gradient becomes the straight line OT. The joulean gradient is the parabola OPX with its maximum of 411.0 degrees cent. The total gradient in the working state is OQT.

The furnace thermal current AB is uniform at 1025 watts, as in the corrected case. The joulean thermal current is the straight line AC, with 1050 watts escaping from each end. The total thermal current in the working state is the dotted straight line hK, with 25 watts leaving the furnace at X, and 2075 watts leaving the open end at O.

The errors due to taking mean resistivities are therefore, in this case, 140 watts at the furnace end, and 156 watts at the outer end. The magnitude of this error tends, in general, to increase with the length of the electrode, the electric current density, the magnitudes of the resistivities, their range of variation, and the furnace temperature elevation. Considering the present imperfection of our knowledge concerning electrode resistivities, it will ordinarily not be worth while to take the extra time necessary for working out the correction-formulas. In most cases the mean resistivities, as used in Mr. Hering's paper, will give satisfactory results.

If we examine formula (29) and consider what cross-section of electrode will minimize the total escape of heat from the outer end, we differentiate (29) with respect to s, and equate to zero in the usual way. This requires that the first term of (29); *i e.*, the furnace flow, shall be equal to the second compound term, or joulean flow. Consequently, in the general case when both resistivities vary, the minimum heat-waste is found when the joulean flow through the external end is equal to the furnace flow. This is the same relation as was stated in Mr. Hering's paper. Whereas, however, the joulean flow through the outer end was pointed out in that paper to be half the total joulean flow with constant resistivities, it is not, in general, half the joulean flow when either one or both of the resistivities can vary.

Within the assumptions to which the above inquiry has been confined, Mr. Hering's first two laws may be amended as follows, to meet the conditions of variable thermal and electrical resistivity.

a. The combined loss through the cold end of an electrode is equivalent to the sum of the loss by heat conduction alone (when there is no current) and approximately half the $I^2 R$ loss, the exact fraction depending on the temperature coefficients of the resistivities. With constant resistivities, the fraction will be one-half.

b. The above combined loss will be least when the loss by heat conduction alone is equal to the joulean loss through the cold end. The total loss will then be approximately equal to the total joulean loss and very little heat will flow into or out of the furnace. With constant resistivities, this resultant furnace flow will be nil.

LIST OF SYMBOLS EMPLOYED

a = the distance coefficient of electric resistivity (1/cm.).
b = the distance coefficient of thermal resistivity (1/cm.).
$A = A_1 + A_2$, an integration constant (degrees cent. per cm. per cm.).
B = an integration constant (degrees cent. per cm.).
I = current strength through electrode (absamperes).
ϕ_x = thermal current in direction OX, through a cross section of the electrode, at distance x cm. from the outer end (abwatts).
$\mathcal{R} = \mathcal{R}_0 + \mathcal{R}_x$ = thermal resistance of the electrode (thermal absohms).
R = electric resistance of the electrode (absohms).
ρ = electric resistivity (absohm-cm.).
σ = thermal resistivity (thermal absohm-cm.).
ρ_x = electric resistivity at distance x cm. from outer end (absohm-cm.).
σ_x = thermal resistivity at distance x cm. from outer end (thermal absohm-cm.).
s = cross-sectional area of electrode (sq. cm.).
T = temperature-elevation of furnace over outer end (degrees cent.).
t_x = temperature-elevation of any point on the electrode x cm. from and above the outer end. (degrees cent.).
v = $X/2$ (cm.).
x = distance from outer end to a point on the electrode (cm.).
X = length of the electrode (cm.).

DISCUSSION ON "MODIFICATION IN HERING'S LAW OF FURNACE ELECTODES," CHARLOTTE, N. C., MARCH 30, 1910.

Carl Hering: In this very able and interesting paper Dr. Kennelly has made a contribution to our useful knowledge on this subject, which is of considerable value to us as engineers, as he demonstrates that certain correction factors in these simple laws of electrode properties, may be neglected in practical work, or if they are to be included then how to allow for them.

This is of special importance because serious doubt was thrown on the usefulness and reliability of these simple laws by criticism from certain academical quarters on the ground that the premises on which they were based did not include an academically rigid consideration of the temperature variations of the physical constants (which by the way would at present be impossible because they are not yet known). None of these academic critics however did or were able to show quantitatively that the alleged error was really large; they condemned the results of this investigation in a wholesale manner, merely because the assumed simplified premises were not academically exact; although I believe none denied that the results were rigidly correct under those assumed premises.

Dr. Kennelly in this paper has therefore come to the rescue of these new laws by showing with the same tools which the academician is so fond of, that the approximation under more exact premises, is very close, thereby assuring the engineer who is designing furnaces that he may feel safe to use the laws as based on the simple conditions, and that he can safely ignore the academic opposition to them.

His paper affords a very good illustration of how the mathematical physicist can perform services of great value to the practical engineer by solving the more intricate mathematical problems and giving the conclusions in simplified and well digested form for direct application to practice. This, in my opinion is putting mathematics to its proper use, namely, as a tool to produce a useful result, as distinguished from a mere form of entertainment of those physicists who are more interested in mathematical intricasies and gymnastics than in useful practical results.

Some of Dr. Kennelly's results confirm in a more positive way the more general deduction made in the original paper, that as the curve representing the losses is very flat at its minimum point, no great error would be committed, as far as this loss is concerned, by any possible and much greater errors in the cross section due to neglecting the minor factors like the temperature corrections, provided only that the results are somewhere near this minimum point; the simpler formulas enable us to get near this point.

One of his conclusions, namely, to the effect that the conditions for a minimum electrode loss and those for no flow at the furnace end, are no longer identical (though still approximately so) when the temperature variations are taken into consideration, has since been confirmed by an entirely different method, and therefore appears to be correct even without his simplifying premise of a straight line heat gradient in the electrode by the ingenious use of which he has succeeded in getting sufficiently accurate results in a case in which the rigidly correct solution becomes extremely complicated. Even when the rigid solution is effected on the basis of straight line laws of variation of the resistivities, it is still only an approximation because it is known that these variations do not follow such regular laws; for graphite for instance the resistivity first falls and then rises again hence the variation even reverses; while for carbon we know it could not fall according to a straight line law because such a line would when prolonged, give a zero and even a negative resistivity which of course would be absurd.

At first thought it seemed that there might be a mathematical inconsistency in assuming as he does, that the heat gradient in the electrode during normal operation, is a straight inclined line, when it is known that this line must be horizontal at the hot end in order to produce the condition of no flow at the furnace end, and really is a parabola. But is seems that this approximate assumption is made only in so far as it concerns the values of the temperature coefficients of the resistivities, and no farther. If so, it is not an inconsistency, but merely means a a slight error in the form of a small per cent of an already small per cent, and therefore can safely be neglected. When an assumption of such a nature serves to greatly simplify an otherwise extremely complex mathematical result, (which another investigator abandoned when he found it too complicated to integrate) it affords another good illustration of the skillful use of mathematics as a tool to arrive at results for use in practice.

I take pleasure in strongly endorsing Dr. Kennelly's use of thermal resistivities (instead of conductivities) and thermomotive forces. I have long used these quantities in my regular work, and would like to have used them in my papers, but I feared that it would meet with disfavor among many who seem to prefer to waste time and brain energy using the more orthodox methods than to reduce these personal losses to a minimum by using quicker and more direct, though unorthodox methods and tools.

President Stillwell: The opportunity for utilizing electric furnaces exists only where cheap power is available. In the case of these southern rivers, which have so widely variable flow, the problem of the utilization of the power developed always raises, not only the question of cost of development, but also the possibilities of finding a market for the power. At Niagara, the company which financed the original development was greatly disappointed by the slowness with which the market developed. It took a long time to convince the people who used steam power in Buffalo that electric power could be substituted to advantage. At that time there was naturally very much greater doubt of the continuity and certainty of transmission than there is today. The result was that at Niagara a number of electrochemical industries were actually developed as a result of the fact that power there could be obtained in large quantities at low cost, and today about two-thirds of the power which is produced by the Niagara Falls Power Company is used in electro-chemical processes, very few of which existed when this power was first made available and attention directed to it.

In certain sections of the south, with its great and comparatively undeveloped mineral resources, there are also water powers in excess of present requirements for existing industrial uses, and we have thought that by directing the attention of the southern members of the Institute in these papers to certain important fundamental facts relating to the design of electric furnaces, some impetus might be given towards bringing the metallurgist and the engineer together in this section to the advantage of the community.

I was told recently that the U. S. Steel Company, in the old factory of the Washburn & Moen Company, at Worcester, is using a very large electric furnace for the production of steel, and that notwithstanding the high cost of power at that point, the improved quality of the steel, the almost absolute immunity from those constituents, such as phosphorus and sulphur, which are harmful in steel for most of its uses, justified this comparatively expensive method of refining the metal.

A paper presented at the Charlotte meeting of the American Institute of Electrical Engineers, March 30, 1910.

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THE PROPORTIONING OF ELECTRODES FOR FURNACES

BY CARL HERING

Introductory. The usual rules for proportioning electrodes for electric furnaces have been based on such factors as allowable current densities, least practicable resistance (hence shortness and large section), lowest heat conduction, the summation of losses due to the electric resistance and to the heat conduction to get the total, etc.

Believing that these laws were not based on correct principles, and were therefore unsatisfactory and perhaps even misleading, and as apparently no one had made a thorough investigation of this subject based on unquestioned fundamental laws, the writer some time ago made a careful study of the true principles underlying the proper proportioning of electrodes, based on indisputable physical laws. The results of this analysis showed that our former rules were not only entirely inadequate, but were in part quite incorrect and led to entirely wrong conclusions. And as the value of the annual loss of energy in such electrodes is very large, the matter of the correct proportioning is of considerable commercial importance as well as of interest to the engineer. This analytical investigation was then supplemented with an experimental one in which the necessary physical constants and the behavior of different electrode materials were determined.

The purpose of the present paper is to give a general review of these investigations from the standpoint of the engineer who is concerned with the proper design and operation of furnaces, and to discuss more particularly the practical bearing of the results of the experimental part, including the proper proportioning of the electrodes, the selection of the best material, the calculation of the losses, the indications of the faults in existing constructions and their remedies. etc.

Some parts of these investigations have been published or are being published elsewhere, to which those interested are referred. The present paper will include only a general summary of these and will discuss more particularly the experimentally determined data not included in the other papers.

Fundamental principles. The fundamental principle of the present analysis of the electrode problem, is that the heat gradient at the hot end should be zero; that is, the line representing it should be horizontal at that end. This means that no heat will then traverse through the hot end, either one way or the other; hence no heat from the furnace or its products is lost through the electrode, and the product can therefore not be "chilled" by the electrode as has often been found to be the case with improperly proportioned electrodes. Such an electrode is a perfect heat insulator, better even than the walls.

This zero gradient can be obtained only by having the temperature of the hot end of the electrode equal to that of the furnace. In the present method this is done by so proportioning the electrode that the current through it will raise the temperature of the hot end to this furnace temperature.

Although the writer's first recommendation of this fundamental principle was met with scepticism and even ridicule, it is now believed to be generally accepted as the correct one. One's first impression, that this would consume much energy, is found to be incorrect; the explanation is briefly, that as the heat near the hot end has no easy means of escape, (for as it cannot get into the furnace it must all flow out at the cold terminal) it will rapidly accumulate, so that a small amount of energy will soon produce a high temperature. Under simplifying assumptions, (and approximately under all conditions*) this state of temperature equilibrium, is found to be also the condition of minimum total loss of energy in the electrode.

Although this way of operating an electrode is quite the contrary to that dictated by prior practice, which was based on the lowest practicable resistance, it turns out to be the most economical, even though it may involve an intentional increase of the resistance loss; it is the total loss which should be considered, as the watts of heat lost either from the furnace or in the electrodes cost the same.

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*Metal. & Chem. Engineering, April, 1910, p. 188.

Another advantage is that the whole interior of the furnace then becomes useful, because a furnace in which there was a chilling action around the electrodes, by a mere change of proportions of the electrodes, based on this principle, can then have its capacity increased to that of its full interior size.

It furthermore means that all the heat escaping at the cold end is then the $I^2 R$ heat. Or inversely, if all the heat escaping at the cold end is the total $I^2 R$ heat, and neither more or less, then the temperature of the inner end will be that of the furnace, and there will be no loss of furnace heat and therefore no chilling.

It is evident that this condition can be reached regardless of how good or bad a heat conductor the electrode material is; even with such a very good heat conductor as copper. Hence, even without any further analysis, this shows the fallacy of the oft repeated and generally accepted statement that a good heat conducting electrode material necessarily chills the furnace, and is therefore objectionable. It will at once be seen that electrodes of good heat conducting materials must simply be made smaller in section than others.

Besides this fundamental principle there are a number of other features in which the writer's conclusions differ very radically from our former practice. The second one is in the determination of the total loss of energy in an electrode. According to the usual former practice, as shown in even very recent papers, the total loss was assumed to be the sum of that due to heat conduction alone and that generated in the electrode itself by the current. The writer found that this also was a fallacy and was not founded on a correct analysis. The true total is the sum of the conduction heat and only half the $I^2 R$ heat, under the simplest condition of constant conductivities and no loss of heat to the walls. This has since been confirmed by others also and is now, it seems, generally accepted. Under the more complicated conditions of varying conductivities, it is claimed by some to be only approximately true, but in any case it is much more nearly correct than the older method.

It is easily seen why it should be so. The heat conducted from the furnace when there is no current, flows over the whole length of the electrode, hence the drop of temperature is proportional to the total flow; but the $I^2 R$ heat is generated throughout the whole length, hence is equivalent to the whole of it entering at the middle and flowing over only half the length, or to half of it flowing over the whole length. Hence as far as the drop of temperature between the ends is concerned, only half of that corresponding to the $I^2 R$ heat must be added to that due to conduction alone.

A third point of difference, and one which is still adhered to tenaciously by some, concerns the current density. This was formerly the basis of electrode design and is still considered so by some writers. The present investigation, however, has shown this to be a fallacy also. It has shown that the current density does not enter as a fundamental factor which determines the proportions. Even more than that; to base the proportions on current densities may even mislead one into using entirely incorrect proportions with unnecessarily large electrodes and losses of energy, accompanied by a false assurance that it is the best that can be done. It may have been found that when certain current densities were exceeded, troubles arose, but in the writer's opinion the mistake made was in attributing them to the current densities instead of to the length; it can be shown that the same current density will cause the electrode to become too hot or too cold, depending upon the length of the electrode. And conversely, for a given length a fixed current density prescribed by rule of thumb may be either much too high or much too low. Current density cannot therefore be a determining factor; it is no more a factor in the proportioning of electrodes than it is in calculating transmission lines, and should be abandoned the same as it was in the latter case years ago.

Since the writer pointed this out, a crude attempt has been made to defend the older practice by claiming rather vaguely that in some way the current density should be modified with the length. This is " beating around the bush " and would be an unnecessarily awkward and roundabout method, even if definite rules which are directly applicable had been given by the defender of that method, which was not the case.

The writer's conclusions are that current densities need not be considered at all as a determining factor, not any more so, and perhaps even less so, than in the calculation of transmission lines. He has operated electrodes very successfully and with the greatest possible economy of power at heretofore unheard-of current densities; and he knows of cases in which far lower current densities were concluded (erroneously) by furnace engineers to have been too high.

The fourth point of difference in the present method is in the resistance. The writer has found that the usual rule, to make it as low as practicable, is a mistake. It can be shown that the resistance for the most economical operation is not at all a matter of choice. It is determined by the conditions of the problem and is fixed by the temperature, current and material; it is different for different materials; hence to try to make the resistances the same for different materials is improper designing.

This investigation, of course, applies to the electrode proper, or what might be termed the essential electrode, or the chief part of an electrode, namely the part which passes through the walls, and in which the coöperation of the two heat flows is the governing feature. Any additional parts within the furnace or projecting beyond the outside of the walls, are not theoretically essential parts even though they may be very necessary in practice; such parts are evidently determined by entirely different conditions and considerations and must be treated apart from that portion which is absolutely necessary to lead the current from the outside to the inside of the furnace. To attempt to combine the various parts of such a longer electrode and to treat them as one in an analysis for finding out the laws governing the proportions, would either be impossible or would at least lead to endless complications rather than to a simplification.

Hence throughout the present paper the proportions of the electrode and particularly the length, refer to this essential part passing through the wall; the prolongations at either or both ends, if any, (as for instance the part embraced by the metallic terminal, or the extra part allowed for feeding) must be determined separately, being governed by entirely different considerations. When the metallic terminal surrounding the outside end is close against the wall and relatively short as compared with the part within the walls, it would probably be sufficient for most practical purposes to consider the electrode proper as ending at the middle of this terminal. And unless the cooling water is very close to the electrode, and the heat resistance between the electrode and cooling water is very low, the temperature at the virtual end of the essential part of the electrode will be higher, and perhaps considerably higher, than the cooling water, hence the drop of temperature in the electrode proper will be less; it will be shown below that the hotter the outside terminal, the smaller the loss in the electrode.

This shows the fifth point of difference from our former views. Instead of trying to keep the outside terminals as cool as practicable, we ought to try so to design them as to let them get as hot as practicable, even to the extent of heating them with a blast lamp, when such heat is cheaper than electric heat. This will economize power, provided of course that the electric heat comes from the electrode proper and not from a poor terminal contact. The section of the electrode, however, becomes larger by raising the outside temperature.

A sixth point of difference from former practice which is brought out by this analysis is that instead of tending to make electrodes large, we should on the contrary try to make them small, as they can then be just as efficient; and there may even be other advantages also, besides economy of material, terminals, etc., in doing so.

Another complete departure from former methods is in the abandoning of the conductivities of the materials as factors in calculating electrodes and electrode losses. The writer found that the desirable qualities of electrodes do not depend on either the electric or the thermal conductivity alone, but on certain relations between the two. The analysis shows that our former deep-rooted conviction that a high heat conductivity is a bad feature for an electrode, is entirely wrong. The fact is, that it may be a good or a bad quality, depending upon the electrical conductivity. Neither alone is a criterion or a measure of excellence, and to consider them so misleads us.

In the writer's method of designing electrodes both qualities have been abandoned entirely as a basis of proportioning, and they have been replaced by two new qualities which are true and correct measures of excellence of those materials when they are used for electrode purposes; moreover they greatly simplify the calculations. Apparently the only objection to them is that they are not yet found in that form in tables of physical properties; they are however easily calculated from the conductivities, if the latter are known. That they are new and unfamiliar quantities will, it is believed, not be considered an objection by those who will take the time to understand their meaning.

These two new measures of electrode qualities are the "electrode voltage" and the "specific cross-section", these specific names having been given them in order to distinguish them clearly from other quantities. They are both measures of physical properties, quite as much so as conductivities, specific heats, specific gravities, etc., and are constants for the particular materials; that is, they are independent of the dimensions. The former concerns the power loss and the latter the size. The lower their values are the better is the material for electrodes. They will be further discussed below.

ANALYTICAL

In an analytical investigation to determine the theoretical relations or laws in a complicated case involving many variable factors, especially in an entirely new field, the writer has followed, and is entirely in accord with, the teachings of such able authorities as Thomson (Lord Kelvin) and Taite, and doubtless of others also; namely, that it is best to solve such a problem first under the simplest possible conditions or premises, as a first approximation, and afterward to consider the refinements (if necessary) as a second or even third approximation. An attempt at the start to solve the complete problem with all its numerous less important refinements, as advocated by some of the writer's critics, would be more likely to obscure and lead us away from those simple and instructive approximate relations, which are often so valuable to the constructing engineer, than to lead us toward them and to point them out to us. A minor factor which might be absolutely negligible in practical calculations may give rise to very great complications in strictly correct algebraic expressions of a desired relation, thereby completely obscuring the more useful approximate one.

Hence in the present investigation, after a number of trials, it was found best first to eliminate all but the main or essential factors by limiting the premises to the simplest conditions. This made it possible to determine the fundamental relations or laws of electrodes, which prove to be very interesting and useful. By proceeding in this way, it was found that most, and perhaps all, of the more important corrections due to the minor factors, like the variations of the conductivities with temperature, could be combined into two experimentally determined coefficients or constants, and by the use of these in the original formulas, all the important, and perhaps even also the unimportant corrections can readily be included. A method was then devised by the writer for determining these constants experimentally, and was carried out by him; the results will be given below. This combination method is believed to be a simpler and more practical way of solving the complete problem with all its intricacies, than the purely analytical one, which even if it were completed, could not be used in practice until certain extended experimental determinations had been made, as no one has yet made them. As the present method of using the simplest possible formulas and embodying all the correction factors in two experimentally determined constants, seems to be not only simple but even more accurate and reliable than the other more complicated method would be, it is believed that the necessity for the other solution and for the long series of experimental determinations, which it is based upon, no longer exists.

The premises of the present simplified analysis are: that the cross-section is uniform; that the two conductivities have the same values over the whole length; that the electrode is heat insulated except at its ends; also that the Thomson effect, the skin effect, and other similar minor factors are neglected. Under these premises the following relations are rigid and exact, and may therefore be called the laws of electrode losses.

Laws of electrode losses:

a. The combined loss through the cold end of an electrode is equivalent to the sum of the loss by heat conduction alone (when there is no current) and half the $I^2 R$ loss.

b. This combined loss will be least when the loss by heat conduction alone is made equal to half the $I^2 R$ loss; the total loss will then be equal to the $I^2 R$ loss, and no heat will be conducted from the interior of the furnace.

c. This minimum loss is dependent only on the material, current and temperature, but not on the absolute dimensions; it merely fixes the relation of the cross-section to the length, but leaves a choice of either; hence

d. For economy of electrode material the length should be made as short as practical considerations permit.

e. For each material there is a definite minimum loss of electrode voltage which depends only on the temperature and is independent of the dimensions or the normal current for which the furnace is designed; hence

f. The best possible electrode efficiency for any material may be determined from the total voltage of the furnace and this minimum voltage due to the material and the temperature, and is independent of the dimensions.

g. The temperatures indicated by the heat gradient of the combined flow are equal to the sums of those of the individual flows.

The proof of these laws is given in a paper by the writer on

"Laws of Electrode Losses in Electric Furnaces",* and need not be repeated here.

The starting point is the fundamental principle, first announced by the writer a year ago as the proper one, namely, that no heat should leave or enter the furnace through the electrode or in other words, that the heat generated by the electrical resistance shall raise the temperature of the hot end to that of the furnace, it is shown that under the given conditions this is also the condition of least total loss.

Watts, a measure of flow of heat. Before giving the formulas the writer desires to explain that it is quite correct, and it simplifies such calculations greatly, to represent and measure a flow of heat in terms of the electric unit watts, instead of in calories per second. A watt is just as correct a measure of a flow or current of heat (calories per second), as an ampere is for measuring a flow of electric current in coulombs per second. Heat is energy, and a rate of flow of heat per second is power, hence it is measurable in units of power like watts. Since the writer called attention to this, others have endeavored to improve matters by calling this unit "watt seconds per second", but this cumbersome name is entirely unnecessary and obscures rather than simplifies our conceptions. It is evident that watts × seconds ÷ seconds = watts. When the heat conductivity of a material is given as 10 watts for an inch cube, it simply means that with one degree cent. difference of temperature between two parallel sides, and perfect heat insulation on the other four, the same amount of energy will flow through as heat, say into water at the cold end, as would enter the water from a coil of resistance wire in which 10 watts were being set free.

In the following, therefore, all flows of heat will be represented in watts, and it is recommended that in future all thermal constants pertaining to electrodes be given in terms of watts instead of calories per second. The conversion factors are: gram calories per second × 4.18617 = watts, and watts × 0.238882 = gram calories per second.

Formulas. The following formulas are the same whether inches or centimetres are used, provided they are employed consistently throughout, including all those constants which are based on dimensions, and which of course will be different; those like the electrode voltage or watts per ampere are, of course, the same in both systems. All the formulas in this paper are in erms of actual units and may therefore be used directly in practice. They refer to one electrode.

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*Trans. Amer. Electrochem. Soc. Vol. 16, p. 265.

Let S = cross-section in square inches;
L = length in inches (the essential length);
I = current in amperes;
W = watts generated electrically in the electrode;
H = heat flow in watts which would flow if there were no current;
h = heat flow in watts which enters the hot end from the furnace;
X = total heat flow in watts leaving the cold end;
T = temperature drop in centigrade degrees between the hot and cold ends;
r = electrical resistivity in ohm, inch cube units;
k = thermal conductivity in watt, inch cube units;
e = electrode voltage in volts;
E = total voltage between the two ends, or the watts per ampere;
s = specific cross-section in square inches;
S' = section in square inches per ampere per inch of length (or in sq. cm. per ampere per cm. length if the other quantities are in terms of centimetres).

In general, the flow of heat in watts at the cold end is

$$X = H + W \div 2 \tag{1}$$

and entering at the hot end

$$h = H - W \div 2 \tag{2}$$

in which

$$H = k\,T\,S \div L \tag{3}$$

and

$$W = r\,I^2\,L \div S \tag{4}$$

The total flow out of the cold end will be a minimum when

$$H = W \div 2$$

Representing this minimum flow by $m X$, then

$$m X = 2 H = W = I \sqrt{2 k r T} = I e \sqrt{T} \qquad (5)$$

this it will be seen does not contain either S or L, which means that this is the same for all dimensions; it includes the condition however that the ratio of the section to the length is

$$S \div L = I \sqrt{r \div 2 k T} \qquad (6)$$

which means that either the length or the section may be made anything one desires, provided only that the ratio is equal to the above. As the length is usually fixed by other conditions this formula is best written

$$S = I L \sqrt{r \div 2 k T} \qquad (7)$$

The electrode voltage is

$$e = \sqrt{2 k r} \qquad (8)$$

and the total voltage is

$$E = \sqrt{2 k r T} = e \sqrt{T} \qquad (9)$$

both of which are seen to be independent of the dimensions or the current, the electrode voltage being even independent of everything except the properties of the material, and hence itself a physical constant. This means that for every material there is a fixed and definite voltage for one degree which voltage is the same no matter what the size of the electrode or the normal current, provided only that it is correctly proportioned so that no heat flows through the hot end.

Conversely, the total voltage E being known, a convenient way is at hand of finding out whether the hot-end temperature of the electrode is that of the furnace or not, as this voltage might be measured without much difficulty during the operation of the furnace; if the measured voltage is found to be less, the electrode is chilling the furnace, if greater, the electrode is getting hotter within the wall than it is in the furnace.

The electrode voltage is that physical constant which is a true measure of the loss of power in an electrode. When multiplied by the square root of the temperature drop and by the current, as shown in (5), it gives the minimum loss in watts which can possibly be obtained with that material, for that current and temperature. Hence if its value is known, it is not necessary to know the two conductivities in order to calculate this loss of power.

The quantity E is measured directly in the experimental determinations described later; hence it is known for each temperature and material. Substituting its value (9) in equation (5) gives

$$m\,X = I\,E \tag{10}$$

That is, the minimum loss in watts may be determined directly by multiplying this value of E by the current; hence the voltage E may be called the " watts per ampere ".

This shows the simplified method suggested by the writer, for calculating these minimum losses. It consists in tabulating for each material the values of E for different temperatures, as obtained directly by experiment (by the method described below); then for any given case, in which of course the current and temperature are given, one needs merely to multiply the corresponding value of E by this current to get the result. This is so simple that it can often be done mentally. The values of the conductivities need therefore not be known.

Returning to formula (7), if I, L and T are made unity, that is, for 1 ampere, 1 in. length and 1 degree cent. of temperature, the resulting cross-section, now represented by s, becomes

$$s = \sqrt{r \div 2\,k} \tag{11}$$

This the writer proposes to call the " specific section ", because it is a physical property of the material, as its value, like that of the electrode voltage, depends only on the relations of other physical properties. It is a true measure of the size of an electrode, of course always under the condition that the electrode operates as was specified. This quantity therefore is the mate to the electrode voltage and determines the size just as the latter determines the loss.

Now let S' be another quantity so that

$$S' = s \div \sqrt{T} = \sqrt{r \div 2\,k\,T} \tag{12}$$

It will then be seen that in the same way and for the same purpose as was described above for E as compared with e, it is possible to determine by direct measurement (by the method described below) the values of this quantity S' for various temperatures and for each material. When these values are tabulated it again becomes an extremely simple matter to calculate the proper cross-section, because

$$S = I\,L\,S' \tag{13}$$

that is, one needs merely to multiply this value of S' from the tables by the current and the length to get the actual cross-section. This quantity S' is therefore here termed the "section per ampere per inch of length". Hence this calculation is also reduced to a surprisingly simple one, provided these tabulated values are at hand. Such a set of values of both S' and E is given below in Table II.

When S' is not known, then

$$S = I\,L\,s \div \sqrt{T} \tag{14}$$

It will be seen that again the two conductivities drop out and need therefore not be known. In the absence of these tables the values of e and s should be used. If they too are unknown the mean conductivities must be resorted to. If in turn these electrode means are not known and the conductivities at the specified temperature are known, the mean values must first be determined from them. If these conductivities vary greatly with the temperature, a closer approximation could be obtained by taking into consideration the mutual effects of these variations on each other and on the mean, as described later in the discussion of the experimental results.

In this connection the writer desires again to call attention to the fact on which particular stress was laid in his first published description of his method, and which fact has been entirely ignored by the critics, that the curve of the combined losses is quite flat at its minimum point. This means that a considerable error can be made in the cross-section without affecting the power loss appreciably; for instance in a certain case an error of 10 to 20 per cent in the cross-section near the minimum point produced an error of only 1 to 3 per cent in the loss. Hence great accuracy in determining the values of these conductivities is not required for engineering purposes, even though to the physicist these slight variations produce great complications in the algebraic analysis. The degree of complication produced by a factor in a rigid mathematical analysis is no measure of its real importance.

Another reason why great accuracy in the values of these conductivities is not necessary for engineering purposes is that they both occur under the square root sign in the formulas used for electrodes (5) and (6); hence if one of them, as for instance the thermal conductivity which is the one least best known, is four times too great, the result will be only twice too great.

Various other relations exist between these old and new quantities which at times are of interest and use. They are easily deduced and are therefore merely summarized here.

$$e = I \div W\sqrt{T} \tag{15}$$

$$e = r \div s \tag{16}$$

$$s = e \div 2\,k \tag{17}$$

Mean values and equivalent electrodes. All the above is based on the premise that the temperature variations of the physical constants may be neglected; this so greatly simplifies the formulas and relations that the numerous useful and interesting results given above, are obtained. They would certainly not have been brought to light from the extremely complicated relations which result when the temperature variations are introduced algebraically. This is the reason why the writer prefers the method of studying a new problem by means of simplified assumptions first, leaving the corrections due to small variations to be introduced afterward as a second or third approximation, if indeed such accuracy is necessary in calculations of furnaces which unlike dynamos, transformers and other electrical apparatus, cannot possibly be built or operated under very exact specifications. Hence great accuracy in the present investigation is merely of academic rather than of engineering interest.

In the complete form of the method as described by the writer in the original paper on this subject and repeated here, the variations of the conductivities are taken care of very effectively and no doubt more effectively than by intricate calculations, by determining the constants under the very same conditions under which they are to be used. This point was also overlooked by the critics. It embodies the desired correction factors in the constants themselves, hence they need no further attention. Even if the values at specific temperatures are known, which is not the case for carbon and graphite, the writer doubts very much whether the final results calculated from them by means of the more involved and decidedly more complicated algebraic relations, would prove to be as close to the actual as they are when determined by the present extremely simple method.

In the present method the values of the conductivities and other deduced factors obtained as will be described, are the means peculiar to electrode conditions. What they really represent are the values of another or *equivalent electrode* the conductivities and other properties of which are the same as these mean values, and are constant from end to end, that is, they are independent of the different temperatures along the electrode.

Such an equivalent electrode will as a whole operate in exactly the same way, and hence, as far as the flows of heat at the two ends are concerned, it is theoretically identical. It differs however in the shape of that part of the temperature gradient which is intermediate between these two end points. Hence, whenever this intermediate heat gradient is concerned and only then, one must consider the nature of the temperature variations. This will be shown below in the discussion of the experimental results.

A brief summary of the discussion which has taken place concerning this and other features of the writer's method, will be given at the end of this paper.

EXPERIMENTAL

Most engineering calculations of structural work are based on the physical properties of materials often called " constants " even though their values vary somewhat; the proper designing of electrodes is no exception. When not done in this way it becomes a process of more or less skillful guessing which ought not to be called engineering. Until these constants are determined, calculations based on them of course cannot be made. At the time when the present investigation was begun some of the necessary physical properties were either not known at all, or known only very vaguely and indefinitely; this refers chiefly to the heat conductivities. No particular need for them had existed, but since it had become possible to calculate electrodes on a rational basis, the need of these constants was felt. The writer therefore undertook a determination of them for graphite, carbon, iron and copper. The tests were made in the well equipped Electrical Testing Laboratories in New York City.

The method used was the one suggested in his recent paper on "A New Method of Measuring Mean Thermal and Electrical Conductivities of Furnace Electrodes."* It is based on the same fundamental principles and formulas as those of this analysis. Briefly it consists in effect in operating a pair of electrodes under conditions approximating as nearly as possible those under which they should (according to this analysis) be operated in practice, namely that the electrodes shall not chill the furnace; or more scientifically speaking, that the heat gradient at the furnace end shall be zero, represented by a horizontal temperature line, in which case there will be no flow of heat into or out of the furnace through the hot end of the electrode.

While thus operating, the current, voltage and cold temperatures are carefully measured for various furnace temperatures. The heat flow is by this method measured electrically in terms of watts before it is heat, thereby avoiding the necessarily cumbersome and often inaccurate measurements of flows of heat in the form of heat. From the data obtained the mean thermal and electrical conductivities or resistivities and several even more important constants are calculated by the formulas given, which are practically the same as those in which they are afterwards used to calculate other electrodes. Further details are given in the above mentioned paper.

The method therefore amounts to measuring the constants of an electrode under actual operating conditions, and when these conditions are what they should be in practice. Hence it is very direct and does not involve any questionable process of determining the constants under one set of conditions and applying them to entirely different ones. The only important difference between the conditions of the test and those of the subsequent application of the constants, is in the dimensions of the electrodes. These constants are specific quantities; that is they are reduced to values per inch or centimetre units, hence they apply equally well to large or small electrodes, if minor effects, such as the differences in the ratio of the surface to the volume, are neglected. If further proof of this is necessary, it has been furnished by Dr. E. F. Northrup, who in an unpublished article has demonstrated that even under the complex conditions of the operation of electrodes, it is strictly correct to apply the constants obtained by this method to electrodes of different lengths or cross sections or both, provided that the temperature conditions at the ends are the same, and that the heat insulation is also relatively the same.*

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*Trans. Amer. Electrochem. Soc. Vol. 16, p. 317.

The constants given by this test are the *mean* values for the electrode *as a whole* and when operating under the proper conditions. The conductivities thus obtained are not necessarily the arithmetic means of those at the ends or even the averages taken at equally spaced distances. They are means peculiar to operating electrodes, and their relations to the end values or to the mean of the values at equally spaced distances, are different for different materials. For this reason the writer has proposed the term " electrode mean " to designate them. They are the correct mean values to be used in the formulas determined by the present analysis, and as it would be difficult to calculate them accurately from values like those given in the usual tables, for different specified temperatures (if such values existed for electrode materials which they apparently do not), they are best determined experimentally by a direct method like the one described, if indeed it is not also an easier and more reliable method than those formerly used; it gives the proper mean values directly, while the other methods do not. While great accuracy in these constants is seldom if ever necessary in practice for calculating electrodes, it is desirable, to use them in an investigation like the present, in which comparisons and other deductions are to be made and in which the behavior of electrodes is to be studied.

The reasons why these mean values are peculiar to electrodes, will be best seen below.

This phase of the subject is discussed more in detail in an article published elsewhere.† It will be sufficient to say here that these means depend upon the distribution of the heat in the electrodes; that is, on the temperature curve. This is different for different materials and depends on the joint coöperation of both the electric and the thermal conductivities, because each affects the other. These means are in fact the values of an equivalent electrode which as a whole would operate exactly like the original one, as explained above. Hence in the present method these differences in the temperature curves are eliminated as far as the action of the electrode as a whole is concerned; they need be considered only in connection with the relations between the electrode and the surrounding furnace wall.

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*Trans. Amer. Electrochem. Soc. Vol. 17, 1910, p 215 bottom.

†Metal. & Chem. Engineering, March, 1910, p. 128.

The details of the determination of these constants are described in a paper to be read before the American Electrochemical Society at its Spring meeting*. The purpose here is to compare and discuss the results, and to endeavor to point out what they teach us. It will be sufficient to say here that the tests were made with care; the results, as far as they go, are believed to be reliable and even more accurate than is required for most practical purposes. Sets of measurements were made for each of several temperatures for each material, and the final result of each run is an average of a number of very closely agreeing sets of readings. The furnace temperatures were kept constant for periods of about 10 to 30 min. to within about 1 per cent and generally considerably less, it being an important feature of this test to reach the stable state of temperature.

The iron and copper electrodes were run to as near their melting points as practicable. The iron had unfortunately been injured slightly by an accidental excessive temperature prior to the last test, near its melting point, hence the values at the highest temperature are not as closely accurate and reliable as the others, but they are probably not far wrong. The same was the case with the highest temperature values for graphite. Allowances for these have been made in the curves. Less care was taken with the lower temperature values as they were of less importance.

Above about 900 degrees cent. the graphite and carbon electrodes began to be affected presumably by the gases in the granular insulating material, (magnesite), probably by the CO from the incompletely calcined carbonate. The results beyond that point were therefore thrown out, and those near it may not be quite correct.

The full lines in the accompanying curve sheets represent the ranges over which the results were actually measured; the dotted lines are exterpolated and therefore are only probable values. These exterpolated values were added here with some hesitancy as the writer is well aware of the possible danger in relying on the extensions of formulas and curves beyond the actual measured ranges. In the present case however the several curves for each material are linked by fixed relations, hence it is not like simply prolonging individual curves; an incorrect extension of one curve will be likely to show on the others, and perhaps in an exaggerated form. For this reason the extension of each one aids in determining the extensions of some of the others. They are therefore probably more nearly correct than mere unguided and independent extensions would be; in fact it seems likely that these fixed relations are far better guides for these extensions than the curvatures of the known parts of individual curves.

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*Trans. Am. Electrochem. Soc., Vol. 17, 1910, p. 151.

In all these curves the exterpolated values were checked at 2000 degrees cent. and 1400 degrees cent. by these relations, and whatever differences were found were distributed over the curves where they corresponded best with the curvatures of the known parts. A second approximation was thus obtained and this was again adjusted, and so on until a final agreement was reached. This care was taken because at present there exist no reliable data concerning these mean values for those temperatures, and it was thought that the exterpolated values were at least better than none at all, as they were not likely to be far wrong. They are offered here merely for what they are worth and nothing more. The tests for determining these constants become tedious for the higher temperatures on account of the oxidation or other forms of deterioration of the carbon and graphite, and the melting of the metals. It may therefore be some time before the tests are repeated for those temperatures. Until then these exterpolated values may perhaps be of some service. Attention may here again be called to the fact pointed out above, that the curve of minimum loss is rather flat at the minimum point, hence quite a large error in the correct proportions will give rise to only a small one in the energy loss; close accuracy in the constants is therefore not necessary.

There may, of course, be radical changes in these physical constants at the melting points of the metals, and at some points at which carbon may change its condition. These cannot be predicted. The present extensions are all based on a regular continuation of the measured relations.

Although all the electrodes were very nearly ⅝ in. in diameter they differed slightly, hence for comparing them more correctly with each other, the results have here all been reduced to a diameter exactly of ⅝ in. For the same reason they have also all been reduced to a constant cold terminal temperature of

100 degrees cent. by adding or subtracting the required amount to both temperatures. The error involved in doing this is no doubt absolutely negligible for the present purposes. The data were obtained from electrodes 8 in. long measured between the furnace end and the furnace side of the water-cooled terminal.

When the method described in this paper is used for calculating electrodes, the important physical constants in these determinations are the electrode voltage and the specific section described above, and others related to them (E and S'). The two conductivities are then eliminated as separate quantities and need not be considered. They have nevertheless been included in the following curve sheets as matters of interest and of use in studying the subject. The original measured data, namely the current and volts have also been added, after reducing the former as described; they lead to interesting and valuable deductions.

As the current densities in some of these runs were extraordinarily high, it may be of interest to add here that the electrodes behaved very well, so well in fact that the writer would not hesitate to use such extreme current densities in regular practice under the proper conditions. The results prove his contention, which has been disputed by others, that the current density is absolutely no factor in the determination of the proportions of electrodes. As the curves for the values of the current densities would be exactly like those for the current, they have not been repeated on the curve-sheets.

Experimental data. The experimental results and the deductions calculated from the data are given in the accompanying Table I which explains itself; the exterpolated data are given in italics so as to distinguish them from the others.

In order to compare and study these data more readily, they have been plotted in Figs 1 to 11. In Figs. 1 to 4 the properties are compared for each of the materials, while in Figs. 5 to 9 the materials are compared under each of the properties. In Figs. 10 and 11 the two most important of these properties are compared; they were omitted from the other sheets for the sake of clearness.

In all the curves the scales give their actual values and not merely relative ones; hence as these scales are very different for the different materials, it is not proper to compare with each other the curves of the same property for the different materials without making due allowance for the different scales; they may be compared directly only as far as percentage differences ar

Length of test electrode 8 inches (20.32 cm.), diameter 5/8 inch (1.588 cm.) section 0.3068 sq. inch (1.9
as the test electrode had been slightly injured. The numbers

Material	Reference letter	Amperes *I*	Volts or watts per ampere *E*	Watts *W*	Furnace temperature, centigrade degrees	Drop in temperature *T*	Electrode voltage; volts *e*	Specific section; square inches *s*	Speci sectio squa centi metr *s*
Carbon....					20	0			
"	*a*	20.9	0.904	18.9	360	260	0.0560	0.0296	0.07
"	*b*	41.0	1.607	65.9	751	651	0.0630	0.0239	0.06
"	*c*	48.0	1.855	89.0	942	842	0.0639	0.0232	0.05
"	*d*	*62.5*	*2.36*	*146*	*1400*	*1300*	*0.065*	*0.022*	*0.05*
"	*e*	*77*	*2.83*	*220*	*2000*	*1900*	*0.0655*	*0.021*	*0.05*
Graphite...					20	0			
" ...	*a*	96.4	0.830	80.0	389.6	289.6	0.0488	0.00677	0.017
" ...	*b*	118.2	1.000	118.1	546.1	446.1	0.0473	0.00685	0.017
" ...	*c*	137.3	1.130	155.2	720.2	620.2	0.0454	0.00695	0.017
" ...	*d**	151.5	1.276	193.3	913.9	813.9	0.0447	0.00722	0.018
" ...	*e*	*198*	*1.52*	*303*	*1400*	*1300*	*0.042*	*0.0073*	*0.018*
" ...	*f*	*240*	*1.79*	*420*	*2000*	*1900*	*0.041*	*0.0075*	*0.01*
Iron.......					20	0			
"	*a*	372.4	0.1435	53.4	397.8	297.8	0.00831	0.00178	0.00
"	*b*	377.8	0.2735	103.4	727	627	0.0109	0.00254	0.00
"	*c*	380.1	0.3206	121.9	911.8	811.8	0.0112	0.00287	0.00
"	*d**	414.5	0.4318	179.	1245	1145	0.0127	0.00313	0.00
"	*e*	*400*	*0.46*	*184*	*1400*	*1300*	*0.0128*	*0.0033*	*0.00*
"	*f*	*420*	*0.61*	*256*	*2000*	*1900*	*0.014*	*0.0037*	*0.00*
Copper....					20	0			
"	*a*	1785	0.0463	82.7	197	97	0.00470	0.000211	0.00
"	*b*	2087	0.0639	133.4	268.5	168.5	0.00492	0.000238	0.00
"	*c*	2351	0.0875	205.7	370.5	270.5	0.00532	0.000268	0.00
"	*d*	2596	0.1253	325.3	541.4	441.4	0.00596	0.000310	0.00
"	*e*	2730	0.1894	517.	837.4	737.4	0.00697	0.000381	0.00
"	*f*	*2820*	*0.31*	*875*	*1400*	*1300*	*0.0086*	*0.00050*	*0.001*
"	*g*	*2850*	*0.43*	*1230*	*2000*	*1900*	*0.0099*	*0.00060*	*0.001*

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ECTRODE MATERIALS

terminal temperature 100 degrees cent. The series marked with an asterisk (*) are not quite as reliable as the others, by exterpolation, and are therefore only approximations of probable values.

Section per ampere per cm. length; square centi-metres S^1	Electrical resistivity; ohm, inch cube, r	Electrical resistivity; ohm, centimetre cube, r	Electrical conductivity; reciprocal ohm, inch cube	Thermal conductivity; watts, inch cube, k	Thermal conductivity; watts, centimetre cube, k	Thermal conductivity; gr. cal. per sec., inch cube	Thermal conductivity; gr. cal. per sec., cm. cb.	Current densities; amperes per square inch	Current densities; amperes per square cm.
	0.00181	0.00460	552						
.00466	0.00166	0.00421	603	0.95	0.372	0.226	0.089	68	10.6
.00238	0.00150	0.00382	665	1.32	0.519	0.315	0.124	134	20.7
.00203	0.00148	0.00377	674	1.38	0.541	0.329	0.129	156	24.2
.00157	*0.00145*	*0.0037*	*690*	*1.46*	*0.57*	*0.35*	*0.137*	*204*	*32*
.00124	*0.0014*	*0.0036*	*710*	*1.54*	*0.61*	*0.37*	*0.144*	*251*	*39*
	0.000337	0.000857	2965						
.001011	0.000330	0.000839	3029	3.60	1.41	0.860	0.338	314	48.7
.000824	0.000324	0.000824	3084	3.45	1.36	0.825	0.324	385	59.7
.000709	0.000316	0.000802	3169	3.26	1.28	0.779	0.306	448	69.4
0.000643	0.000323	0.000820	3098	3.10	1.22	0.740	0.291	494	76.5
.00051	*0.00031*	*0.00079*	*3200*	*2.95*	*1.16*	*0.71*	*0.28*	*645*	*100*
.00044	*0.00031*	*0.00069*	*3220*	*2.70*	*1.06*	*0.65*	*0.25*	*781*	*121*
	0.0000058	0.0000148	171800						
000262	0.0000148	0.0000375	67700	2.34	0.919	0.559	0.219	1214	188
000258	0.0000278	0.0000705	36020	2.15	0.844	0.513	0.202	1231	191
000256	0.0000323	0.0000822	30910	1.96	0.769	0.468	0.184	1239	192
000235	0.0000399	0.0001015	25030	2.04	0.801	0.487	0.191	1351	209
000232	*0.000043*	*0.000108*	*23500*	*1.92*	*0.76*	*0.46*	*0.180*	*1300*	*202*
000215	*0.000052*	*0.000132*	*19200*	*1.9*	*0.75*	*0.45*	*0.178*	*1370*	*212*
	0.00000066	0.00000167	1524000						
0000545	0.00000100	0.00000253	1005000	11.12	4.37	2.66	1.043	5819	902
.0000467	0.00000117	0.00000298	851800	10.32	4.06	2.47	0.969	6804	1054
.0000414	0.00000143	0.00000362	700800	9.92	3.90	2.37	0.931	7662	1188
.0000375	0.00000185	0.00000470	540200	9.61	3.78	2.30	0.902	8462	1312
0000357	0.00000266	0.00000676	375940	9.14	3.59	2.18	0.858	8899	1379
000035	*0.0000043*	*0.0000109*	*233000*	*8.7*	*3.4*	*2.08*	*0.82*	*9200*	*1430*
000035	*0.0000059*	*0.0000150*	*170000*	*8.3*	*3.3*	*1.99*	*0.78*	*9300*	*1440*

[Hering 504]

concerned. In the second group, Figs. 5 to 9 all the results of one kind are reduced to the same scales, and may therefore be correctly compared quantitatively.

All these data refer to electrodes when operating under the condition that the hot end is raised by the current to the exact furnace temperature, and when the electrode, therefore, does not abstract any heat from the furnace. The values of all the specific properties (resistivities, conductivities, electrode voltages and specific sections) are the means under electrode conditions for the electrode as a whole; that is, they are the values of an equivalent electrode which as a whole will operate like the original one, but in which these properties have the same values throughout its entire length. The values for the currents, watts and current densities apply of course only to the particular size of the electrode tested and will be different for electrodes of other dimensions. The voltages, however, apply also to any other sizes of electrodes and to any other currents, provided only that the electrode is properly proportioned and is operated under the normal specified conditions and with the normal current.

Besides the actual numerical values of the various quantities, the point of special interest in this set of curves is whether the specific properties (that is, the properties per unit conditions) are sufficiently near to constant to be assumed so in ordinary practice, and also whether they rise with the temperature or fall, as this makes a difference in their behavior.

Carbon. Fig. 1. The current curve rises rapidly and nearly in proportion to the temperature. This means that changes in the current will produce nearly proportionate changes in the hot-end temperatures, hence variations in current affect the losses considerably, and a current which is considerably greater than the normal for which the electrode was designed, will tend greatly to overheat the electrode within the walls.

The watts increase nearly according to a diagonal line, as with all the other materials tested, except that for carbon there is a more pronounced deviation at low temperatures, which is also seen in some of the other curves, indicating that the properties of carbon follow somewhat different laws at the lower than at the higher temperature ; or perhaps, that at the higher temperatures, they follow laws similar to those which other materials follow at the lower ones.

The electrical resistivity diminishes, at first more rapidly, then less so, tending to become more nearly constant. A decreasing resistivity means that as the current heats the electrode, the heat generated per inch will become less and less at the hot end and relatively greater at the cold end, than it was before; hence the colder half will be heated more rapidly. This in turn signifies that the heat gradient will tend to approach a horizontal line from the hot end to near the cold one, and will

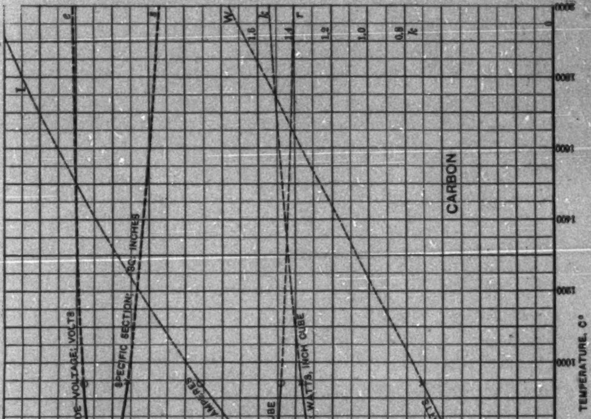

FIG. 1.—Electrode properties of carbon

then drop suddenly. Or in popular terms, the furnace heat will follow the electrode deeper into the walls. This seems to be one of the causes of the burning of the furnace wall in high-temperature furnaces in which carbon electrodes are used. A falling resistivity is therefore an undesirable quality for electrodes.

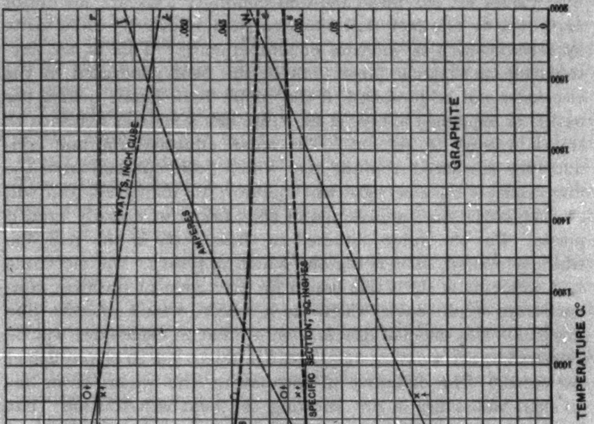

FIG. 2.—Electrode properties of graphite

A rapidly rising one would be far better; this is the case with iron.

The thermal conductivity increases (it does not decrease as has been claimed by others) at first more rapidly, then less so, also tending to become more nearly constant. The surprisingly high values for the mean thermal conductivities are no doubt explained by the fact that the electrical resistivity falls quite appreciably with an increase of temperature. This in an electrode means that the larger half of the heat generated in the electrodes will be produced in the colder half, hence nearer the outlet, as explained above; it therefore has a shorter distance to travel in order to get out. The mean effective thermal conductivity calculated from the heat which flows out and from the dimensions of the electrode will therefore be increased, and will even be larger than an average of that taken at equally spaced points. But the value obtained in these tests is the real one which is wanted, as it is the one which applies to the electrode as a whole; it is the value which an electrode of uniform conductivities would have, which, as a whole, would operate like this one. This unequal distribution of heat in electrodes will be discussed by the writer more in detail in an article to be published elsewhere.* The difficulty in calculating the mean from individual values lies in not knowing the heat distribution, that is, the temperature curve; also in the fact that these individual values for different temperatures have not yet been determined. The writer for these reasons recommended the present method as the more direct one by which to get the final results in the form in which they are wanted.

A rising thermal conductivity is an undesirable feature for electrode materials, as it tends to force the higher temperatures nearer to the colder end. Carbon unfortunately combines this feature with a falling resistivity, both of which conduce to the same undesirable result.

The curves for carbon furthermore show that the electrode voltage, which is a true measure of the power loss, also increases with the temperature, but the rate is slower and slower, tending to constancy. It will be shown later that there are reasons to believe that it may even reverse again and fall at still higher temperatures. The loss in carbon electrodes therefore increases not only with the temperature, but also per degree of temperature; at least for these ranges. The chief conclusion, as far as our present knowledge goes, is that probably no great error would be made by assuming this important quality to be practically a constant, namely about 0.065 volt.

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*Metal. & Chem. Engineering, March 1910, p. 128.

The specific section, which is a true measure of the size of an electrode, decreases rapidly at first and then more slowly, showing that carbon electrodes become relatively smaller for the higher temperatures; they are even smaller per degree at the higher temperatures. This is a good feature, and especially so for carbon because such electrodes are much larger than those of other materials, as will be seen later.

The electrode voltage and the specific section, are properties of the material, just as the specific resistance is, and if their values are constant or virtually so, calculations are simplified. The curves show that for most purposes in practice they may be assumed to be virtually constant for the higher values of this range of temperature.

The curves of the total voltages and of the actual size of the electrodes, being the ones which are the most important in practice, have for clearness been drawn apart from the others and will be discussed below in connection with Figs. 10 and 11.

The comparison of the quantitative values of the properties of carbon with those of other materials, is best made later in connection with Figs. 5 to 9.

Graphite. Fig. 2. The current curve rises more rapidly at first than for carbon, and in this respect graphite apparently possesses properties more like those of the metals. After this rise at the lower temperatures, it seems to approach more nearly to a straight line. The inclination of the latter part is less than for carbon, which indicates that for the same proportionate change in current the change of temperature produced thereby will be greater for graphite. From this it would appear to follow that a graphite electrode is more sensitive to changes of current than is one of carbon.

The curve of watts is practically a diagonal line, which shows that the watts lost in a given electrode will increase very nearly in proportion with the temperature drop, due to the current.

The mean electrical resistivity decreases slightly at first, and then seems to tend to constancy, at about 0.00031 in inch units (0.00081 in cm. units). It varies considerably less than for carbon, therefore the heat generated in the electrode will show a tendency to be more evenly distributed along the length, although the greater half of the $I^2 R$ heat is as in carbon, generated in the colder half of the electrode. Hence graphite stands between carbon and the metals.

A comparison of these mean values with those obtained by others when the whole rod is at the same temperature is of interest. It shows that these mean values are higher than the arithmetical means between the two extremes. This appears to be due to the fact that owing to a more rapidly decreasing thermal conductivity, the heat is forced back toward the hot end by the changes in thermal conductivity, more than it is forced to the cold end by the changes in the electrical conductivity. The result is that the average between the extreme temperatures would be greater than the actual; hence the mean resistivity found in these tests should be greater, which is the fact, if these data are correct. This places graphite among the metals in this desirable quality of forcing the heat back to the hot end.

The curve for the thermal conductivity shows that it falls as has already been stated. In this feature graphite differs decidedly from carbon (for which this curve rises) and is like the metals. The thermal conductivity falls more rapidly at first and then displays a tendency to become more nearly constant. Its rather high value is due partly to the falling electrical resistivity, as was explained above for carbon. It will be seen below that this brings its mean value even above that of iron, which has a rapidly rising resistivity.

The electrode voltage falls slightly, but seems to tend to what for all practical purposes may be assumed to be constant at about 0.040 to 0.045 volts. As this is a measure of the loss, it follows that the loss per degree diminishes slightly with the temperature instead of increasing, as it does with carbon. Graphite, therefore, is relatively to the temperature, more economical of power at higher temperatures than it is at the lower ones. This is due to the somewhat rapidly falling thermal conductivity.

The specific section is practically a horizontal line, and consequently may be assumed to be constant at about 0.0070 in square inches. This means that the size of the electrode relatively to the temperature is practically the same at high and at low temperatures; it does not decrease per degree, as with carbon, but even at the higher temperatures it is still much smaller. These comparisons are best seen below in other sets of curves.

Iron. Fig. 3. The current curve shows a marked peculiarity in that it is practically a horizontal line, differing radically in this respect from carbon and graphite. This is due no doubt to the very rapidly rising resistivity. As the hot end becomes hotter the resistance rises so rapidly that it cuts down the current again. Such an electrode is therefore nearly self-regulating for a constant current. A slight increase of current causes a very great rise in temperature. This fact was not fully realized during the progress of the test, in which the current was at one time raised too high, which apparently melted or perhaps even volatilized the hot end; this occurred before the run at the highest reading, hence the values obtained for the last point are not as good as the others, and were given less weight. After the test bar had been removed it was found that it had been melted at the hottest point and had even partly disappeared. This must have happened before the last run was taken, as that was still below the melting temperature. Anyone who repeats this test should be very careful to increase the current but very little at a time, and should not try to hasten the time of reaching the steady state by a temporary excessive current.

This peculiar property of iron, to change greatly in temperature with slight increases of current, also interfered with the intention to avoid the region of the recalescent point, about 700 degrees cent., as it was to be expected that the electrical and thermal conductivities might also take part in the peculiar physical pranks which iron plays at that temperature. It is doubtless due to this recalescent point that the curves are not as regular as are those of the other materials. They have a noticeable hump at about 700 degrees cent. But notwithstanding these disturbing factors, the general trend of the curves enables instructive results to be deduced.

In the exterpolated (dotted) parts of these curves, it has been assumed that the laws of variations continue to be about the same. It is not unlikely, however, that with materials which melt, like metals, as distinguished from carbon and graphite, there may be decided changes of these physical properties at the melting point. This can be determined only by experiment, and tests with molten columns the cross-section of which must remain constant, become difficult. Moreover, unless they were made on a large scale they would be seriously interfered with by the so-called " pinch effect ", which would break the column unless it was very securely confined. Under the circumstances the exterpolated values may be of at least temporary use until someone has made the actual tests. But it should be remembered that they are nothing more than exterpolations.

The curve of watts is as usual virtually a diagonal

The electrical resistivity rises greatly, and roughly in a straight line with only an indication that the rate probably falls at higher temperatures. This rapidly increasing resistivity is a very desirable feature for electrodes, as it forces the heat back to the hot end, as was explained above.

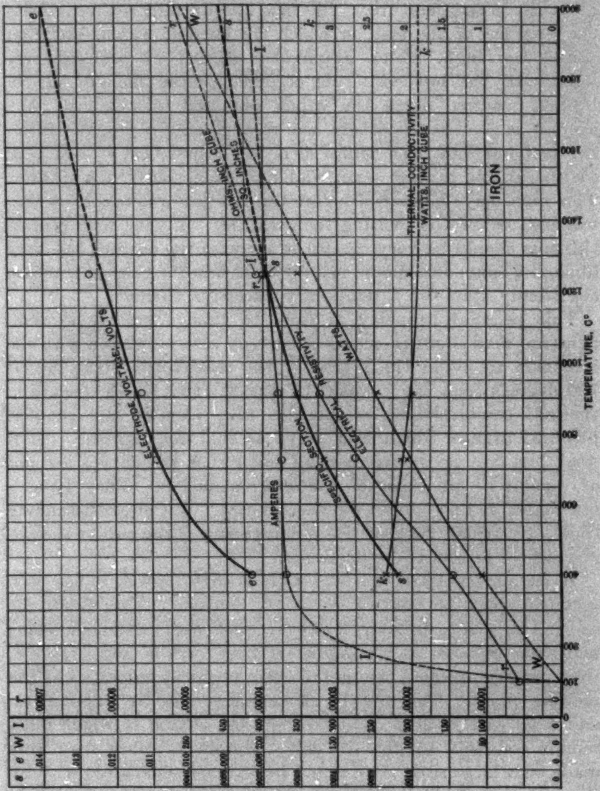

FIG. 3.—Electrode properties of iron

The thermal conductivity falls, which is also a desirable feature. It is of interest to note that for iron both conductivities vary in the desirable way, while for graphite only one does (the other however being nearly constant), and for carbon, they both vary in the undesirable way. Although the thermal conductivity of iron falls, the amount is but slight and it may be assumed

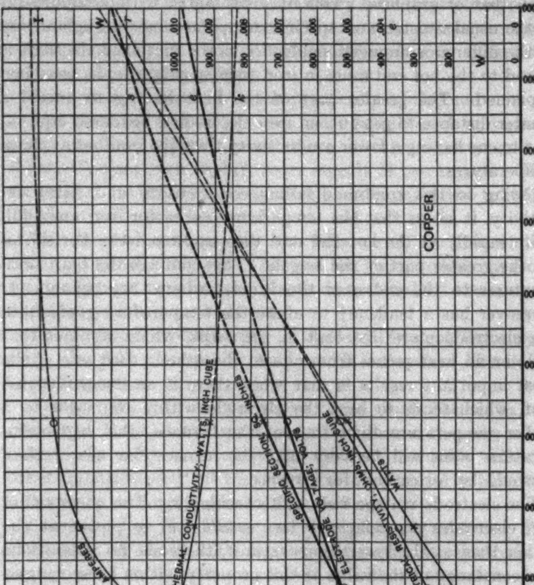

Fig. 4.—Electrode properties of copper

to be practically constant at about 1.9 to 2.0 in watts, inch cube units.

It will be noticed that the mean thermal conductivity is less than that of graphite. This may not agree with comparisons of the usual constants at specified temperatures; the explanation of the difference unquestionably lies in the fact that the heat is forced to the hot end more in iron than in graphite, as has been explained. The greater part of the heat having to travel a greater distance to get out, an iron electrode is rendered equivalent to one having a lower conductivity than the iron has at those temperatures.

Owing to this combined falling conductivity and rising resistivity, it seems that the temperature curve for iron must fall quite rapidly at the hot end and then approach the horizontal for the greater part of the length. This confines the high temperatures to the end near the furnace where they belong. It moreover has a tendency to make the temperature gradient in the electrode more like that in the walls, which signifies that little or no heat passes from one to the other. But one of the most important results is that when there is an excessive current, which tends to heat the electrode within the walls to a higher temperature than that of the furnace, this high temperature point will be very near the furnace, far nearer than it would be for carbon, for instance.

The electrode voltage rises quite decidedly. This means that iron electrodes are relatively less economical in power at the higher than at the lower temperatures; there are no indications of a constancy of the value of this property within these ranges.

The specific section also rises at about the same rate, showing that the size also becomes less favorable at the higher temperatures.

The test bars were cold rolled, mild steel.

Copper. Fig. 4. The tests with the copper electrodes were the best of the series. This was due partly to the fact that the currents, being very large, were better adapted to the output of the dynamo; partly to the fact that copper had a thermal conductivity so very much better than that of the surrounding heat insulating material, that the proportion of the loss to the surroundings was least; and lastly, because it was the last test of the set and the writer was enabled to embody the experience gained in testing the other materials.

The current curve rises extremely rapidly at first and then apparently tends rapidly toward the horizontal; it seems to be similar in shape to the one for iron at lower temperatures. It therefore appears that this shape may perhaps be characteristic of the metals. The last point was very near the melting point. hence the exterpolated values are based on the possibly incorrect assumption that no radical changes take place in these properties at the melting point.

The curve of watts is again practically a diagonal.

The electrical resistivity rises very rapidly and in virtually a straight line; copper resembles iron in this property, and the resistivity rises even slightly more rapidly in percentage. What was said about iron in this respect applies therefore also to copper. The heat will again be forced to the hot end.

The thermal conductivity also falls, as in the case of iron, only to a greater degree. This and the rising resistivity should make copper a very suitable electrode material for the temperatures for which it could be used.

The electrode voltage rises in almost a straight line proportion. So does the specific section. It is therefore like iron in these respects.

Comparisons. In all the above curve sheets the scales were chosen as large as the space permitted, hence they are all different. In order to compare the different materials with each other quantitatively all the curves for each property have been redrawn to uniform scales in Figs. 5–9.

Current. Fig. 5. These curves explain themselves. They show that at about 1500 degrees cent. a graphite electrode will carry over 3 times as much current as will one of carbon of the same size; iron will carry over twice as much as graphite or nearly seven times as much as carbon; and copper is enormously better than any of the others, its current capacity being about 45 times that of carbon or 14 times that of graphite. With what losses these electrodes carry these currents will appear later.

The curves also show a tendency to become horizontal. The actual numerical values refer to ⅝-in. round electrodes and to no others, although relatively the currents would always have the same ratios.

Current densities. The cross-sections in all the test rods being the same, these curves also represent the relative values of the current densities. The actual values are given in Table I. Some of them will be seen to be exceedingly high.

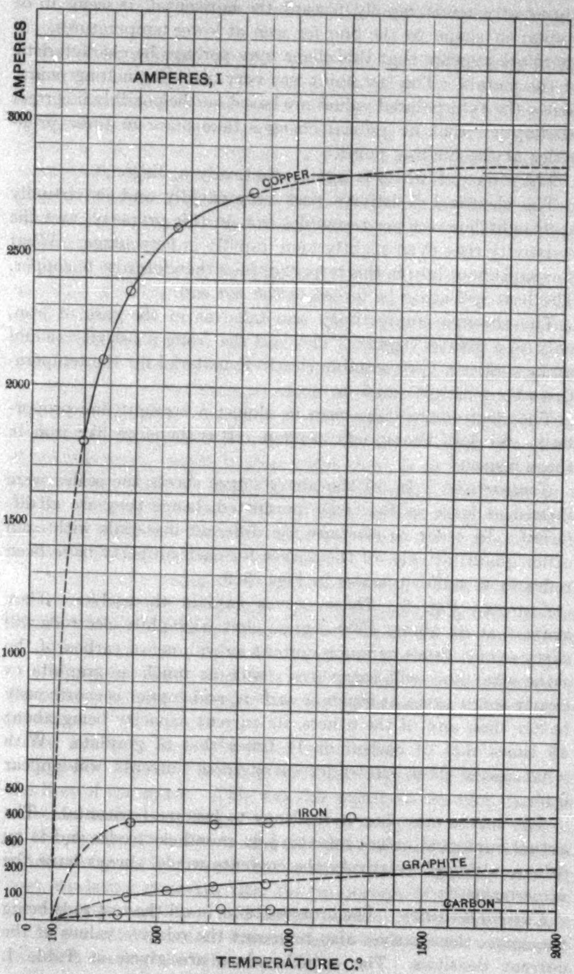

FIG. 5.—Current for different materials

Watts. Fig. 6. The curves for all four materials are seen to be nearly diagonal lines, indicating that the watts increase nearly in proportion to the temperature required. In order to show how little they differ from the true diagonals, the latter have been added as thin lines to the last points. The difference is greatest with carbon. It can be shown that in so far as the real curve differs from the exact diagonal, in so far does the thermal conductivity vary from a horizontal line, that is, from constancy; if these curves approach the diagonal more nearly for the higher temperatures, as they seem to, it means that the thermal conductivities approach constancy for those higher temperatures.

Moreover if the bend is above the diagonal as it is for copper, graphite and iron, it signifies that the thermal conductivity falls, while if below, as for carbon, it rises. Furthermore, it can be shown that the thermal conductivity is proportional to the tangent of the angle which the diagonal to any point makes with the horizontal.

Further than this, the curves should not be compared, as they might mislead. Quantitatively they refer only to those particular electrodes ⅝ in. in diameter, and to no other size. While the watts lost for copper are very much greater than for carbon, the current delivered was also far greater, and the relative loss was far less than for carbon. This is shown better in the later curves.

Electrical resistivity. Fig. 7. These curves show strikingly the quantitative relations, it being nearly impossible to show copper and carbon on the same sheet. A low electrical resistivity is a desirable quality in electrodes, both in economy of power and in the economy of materials. It shows why copper is so very much better than carbon, when it is possible to use it. Iron is near copper, and graphite is much nearer the metals than carbon. A rising resistivity is a good feature while a falling one is a bad one.

An interesting point is that the line for carbon falls rapidly, that for graphite also falls but very slightly, while those for the metals rise. Their relative inclinations make it appear as if they tended to meet at some very high temperature in a common point somewhat below graphite, at which point they would all have the same resistivity. At 1400 degrees cent., the relative values are about: copper 1, iron 10, graphite 72, carbon, 340.

Thermal conductivity. Fig. 8. The thermal conductivities differ far less than the electrical resistivities; moreover the usual order is here reversed, graphite being now next to copper. They again all seem to tend to meet in a point, this time iron being the more central one. The relative values at 1400 degrees cent. are about: copper 1, graphite 0.34, iron 0.22, carbon 0.17. It may be repeated here that a falling thermal conductivity is a good feature and a rising one is a bad one; also that a high thermal conductivity reduces the size of an electrode but increases the loss; hence it is a good or a bad quality depending upon which of the two economies one desires. There are other properties which are better measures of excellence of an electrode material; they will be discussed below.

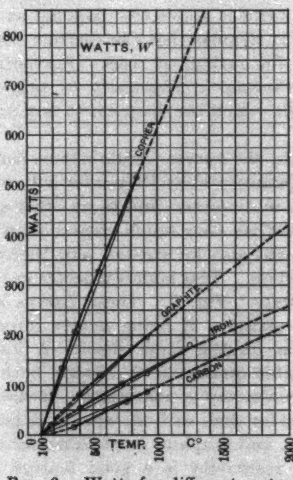

FIG. 6.—Watts for different materials

Electrode voltage. Fig. 9. This is the specific property which is a true measure of the minimum watts lost in an electrode, when it is properly proportioned. Its significance has been described above.

The curves are shown in thin lines. They all show a tendency to rise except for graphite which alone possesses the good property of a falling curve. As all these specific quantities seem to tend to meet at some very high temperature, it may be that carbon which is the only exception, will also fall again at higher temperatures, as indicated.

Iron is now nearly as good as copper and much better than graphite, although the difference seems to grow less at higher temperatures. The lines for graphite and carbon depart at first, but then remain nearly parallel. The relative values at about 1400 degrees, are about: copper 1, iron 1.5, graphite 5, carbon 7.5.

Specific section. Fig. 9. This is the specific property which is a true measure of the size of an electrode, when properly proportioned. Its significance has been described above. The curves are shown in heavy lines. They all tend to rise except for carbon; and again they seem to tend to meet. Copper as usual makes the best showing, and graphite is nearer the metals in this respect than it was for the electrode voltage. Carbon is far from the others, showing that such electrodes must be made very much larger. For about 1400 degrees cent. the relative values are about: copper 1, iron 6.6, graphite 14.6, carbon 45.

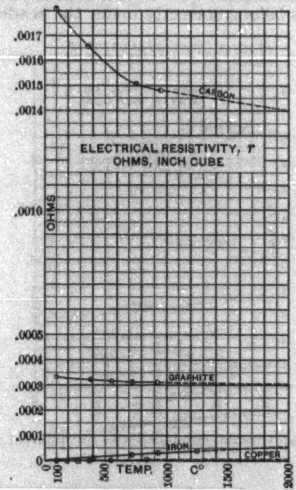

FIG. 7.—Mean electrical resistivities for different materials

These two qualities have been drawn on the same sheet to facilitate comparisons. Carbon electrodes are seen to be both large and wasteful of power, those of graphite are much smaller and while they consume less power, the difference is not as great as that in the sizes. Copper is best in both respects, and iron comes next in both qualities, being also better in both than graphite, particularly in the economy of power.

Actual losses and sizes. Figs. 10 and 11. The electrode voltage and the specific section are the two physical constants which the writer suggests using instead of those formerly employed. Like most other physical constants they vary somewhat with the temperature, though some of them only very slightly; but they nevertheless belong correctly under the heading of physical constants, which can for many calculations be assumed to be constant, or have the differences allowed for, just as is done with resistivities in ordinary electrical conductors.

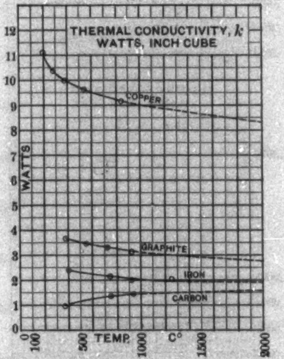

Fig. 8.—Mean thermal conductivities for different materials

But as was explained above, the usually required calculations may be considerably simplified and reduced to a mere simple multiplication, by using instead a tabulated set of numbers. These are no longer "constants" in the usual sense of the term, because from their very nature they must have greatly different values for different temperature ranges, although for some materials and ranges the curves representing them are very nearly straight lines.

If, therefore, the designer has such a table of values at hand, he will no doubt prefer those values to using the physical constants. These two sets of figures give the watts per ampere, and the square inches of section per ampere per inch of length, for each temperature. Hence to find the minimum loss in watts for any given material and temperature (the cold terminal temperature being 100 degrees cent.) one merely multiplies the corresponding number of " watts per ampere " from the table, by the current in amperes, while to find the proper section in square inches it is necessary only to multiply the corresponding " section per ampere per inch length " by the current and the length in inches. The calculations are so simple that they may in many cases be made mentally. These values are given in Table II and are shown graphically in Figs. 10 and 11.

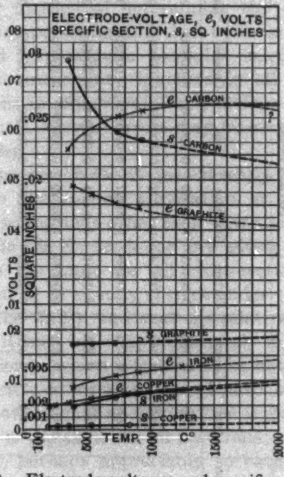

FIG. 9.—Electrode voltages and specific sections

As shown above, the watts per ampere are in fact merely the voltages (in volts) between the two ends of an electrode when operating under the condition in which there is no loss of furnace heat. Hence these are not deduced figures, but are actually measured during the test, (being half the measured voltages of the two electrodes), while the figures for the sections per ampere

TABLE II

CONSTANTS FOR CALCULATING ELECTRODES

Temperature		*E* Watts per ampere				S^1 Square inches per ampere per inch length				S^1 Square centimetres per ampere per cm. length			
Cent. degrees	Fahr. degrees	Carbon	Graphite	Iron	Copper	Carbon	Graphite	Iron	Copper	Carbon	Graphite	Iron	Copper
400	752	1.00	0.85	0.145	0.095	0.00165	0.00040	0.000103	0.000016	0.0042	0.00100	0.00026	0.000041
600	1112	1.38	1.04	0.225	0.140	0.00114	0.00031	0.000102	0.000015	0.0029	0.00078	0.00026	0.000037
800	1472	1.68	1.19	0.295	0.184	0.00090	0.00027	0.000101	0.000014	0.0023	0.00068	0.00026	0.000036
1000	1832	1.93	1.32	0.350	0.226	0.00076	0.00024	0.000098	0.000014	0.0020	0.00061	0.00025	0.000036
1200	2192	2.15	1.43	0.410	0.270	0.00069	0.00022	0.000094	0.000014	0.0018	0.00056	.00024	0.000035
1400	2552	2.36	1.52	0.460	0.310	0.00062	0.00020	0.000092	0.000014	0.0016	0.00051	0.00023	0.000035
1600	2912	2.53	1.62	0.510	0.351	0.00057	0.00019	0.000089	0.000014	0.0014	0.00048	0.00023	0.000035
1800	3272	2.68	1.71	0.565	0.391	0.00053	0.00018	0.000087	0.000014	0.0013	0.00046	0.00022	0.000035
2000	3632	2.83	1.79	0.610	0.430	0.00049	0.00017	0.000085	0.000014	0.0012	0.00044	0.00021	0.000035

per inch length are merely the cross sections of the test rods divided by the length of the electrode (half the length of the double ones used in the test) and by the current.

It will be seen therefore that it is not at all necessary to determine or even to consider either the electrical or the thermal conductivity in electrode problems, if these simple data are at hand. And the writer's conclusions therefore are, that as little or no reliable data of any kind exists for the higher temperatures, and must therefore be ascertained, it is much simpler to determine and use these two new factors, instead of determining and using the mean conductivities. It is also infinitely simpler than the former method of determining the conductivities at each of various temperatures and then by means of more or less complicated and approximate formulas calculating the final results, with the uncertainty involved in all approximate algebraic deductions in which we do not always know how much the originally small, allowed errors may be magnified during the algebraic processes.

The writer's present method goes directly from the experimental result to the desired application in practice, without involving any assumptions other than that the *relative* distribution of the heat in the electrode for any given material and end temperatures, is the same for all cross-sections and lengths, (which is believed to be exactly correct under the assumption of no heat loss to the walls), and that the relative heat loss to the walls, whatever it may be, is approximately independent of the lengths and sections, (which is known to be not exactly true but probably sufficiently so for all practical purposes).

It should be noticed that no assumption is made that the heat loss to the walls is the same for all materials; on the contrary it will be different, perhaps appreciably so because, as was seen above, some materials (like carbon) have the property of forcing the high temperature toward the cold end, while others (like iron) force it back to the hot end. For this reason the temperature gradients will be quite different in the two cases, and the loss to the walls, if it is large enough to be considered at all, will therefore be different for different materials; but in the present method this difference is taken care of in the tabular data, and needs no further consideration.

The curves for these two final quantities are given apart from the others in Figs. 10 and 11. In Fig. 10 they have been drawn to different scales so that they are nearly superimposed, thus enabling their relative inclinations or percentage values to be compared better with each other, while in Fig. 11 they have all been drawn to the same scale, so that they may be compared quantitatively.

In Fig. 10 it will be seen that the curves E, which measure the minimum loss, or the watts per ampere, all have a family resemblance, except in the case of graphite; in fact with slight changes in the scales, those for iron, copper and carbon may nearly coincide, except at their lower temperature values, and this difference may be due to the experimental determinations which were not carried out quite as carefully at the lower temperatures for carbon and iron, as for copper. Even graphite might perhaps be brought into line by a change in the horizontal scale, which would mean that the temperature would have to be multiplied by a coefficient, or have a different exponent.

This family resemblance, and the fact that all these curves must have a zero and an infinite value, of course suggest the possibility of a common formula for all, differing only in its coefficients. But this is beyond the purpose of the present paper; the results obtained in this interesting direction will be made the subject of another discussion.*

The marked difference of the graphite curve means that the losses in graphite electrodes do not grow as rapidly with the temperature as they do for all the other materials. This, of course, is a very good quality, especially for high temperature furnaces. For all the others the relative increase of this loss is about the same. It is of interest to note that copper and carbon, the two extremes in all other comparisons, are here very nearly alike in their percentage variations.

A comparison of these same curves E in Fig. 11, (the heavy line curves) shows the quantitative relations of the actual losses per ampere. The much greater loss for carbon is quite striking; but of course there are many cases in which metals are excluded by the very nature of the furnace. Consequently, tempting as it may be, the good quality of the metals cannot be taken advantage of. The relative values at 1400 degrees cent. are about: copper 1, iron 1.5, graphite 5, carbon 7.5; the same, of course, as for the electrode voltage.

The loss for carbon is seen to be 1.55 times that for graphite. This is interesting in view of the claims that have been made that graphite is more wasteful of power than is carbon, even ten times as bad. Hence either the experimental data on which that result was based were in error, or the method of deducing the result from them was incorrect; or else the curves change very radically at the higher temperatures, which seems hardly likely. If the present exterpolations are correct, this difference in favor of graphite becomes even greater at the higher temperatures.

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*Trans. Am. Electrochem. Soc., Vol. 17, p. 171.

Returning to Fig. 10, the thin line curves S' (the section per ampere and per inch) will also be seen to have a family resemblance, and as they also must have values for zero (100 degrees in this case) and infinity, the possibility of a general equation differing only in coefficients or exponents, suggests itself for this relation also.

If equations can be deduced for both S' and E, it will be possible to calculate both the conductivities from them, as one is proportional to the product, and the other to the quotient, of the conductivities. The coefficients for S' and E are, of course, determined experimentally, as in the present case, and the conductivities will therefore be functions of these coefficients.

The exception in the S' curves is iron, but in general the two metals are similar to each other, as are the two non-metals, the two pairs differing somewhat.

Comparing them quantitatively in Fig. 11, the family resemblance is again apparent, the curves being evidently asymptotic to both ordinates, care being taken to deduct the 100 degrees cent. for the cold terminal temperature.

Carbon electrodes are again shown to be far larger than the others. The relative values at 1400 degrees are about: copper 1, iron 6.6, graphite 14.6, carbon 45, the same as for the specific sections. In this feature graphite is more like the metals and differs more from carbon than in the losses. The section for carbon will be about 3 times that for graphite. This difference in size, however, seems to diminish for higher temperatures, if the present exterpolations are correct.

Comparing both these important factors, it will be seen that graphite is better than carbon in both loss and size, especially in size. Copper is best in both and carbon worse in both, while iron is closer to copper in both than it is to graphite.

This final comparison is shown in a practical way in Fig. 12, in which the sizes and losses in electrodes of the different materials are drawn to scale for a given case, in which the current is assumed to be 10,000 amperes and the end temperatures 1400 degrees cent. and 100 degrees cent.

In the first set, to the left, the length is made the same for all, namely 10 in., hence the sections will be different, and in the proportions of 1, 6.6, 14.5, and 45, the same as above given. The actual sizes in square inches are: copper 1.38, iron 9.16,

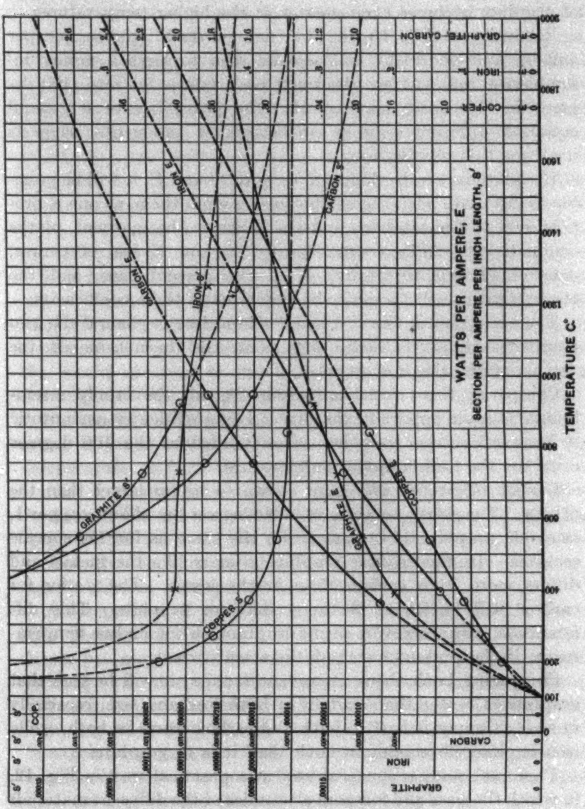

FIG. 10.—Losses and sizes; superimposed

graphite 20.1, carbon 62. It will be seen that the proportions for carbon are practically impossible.

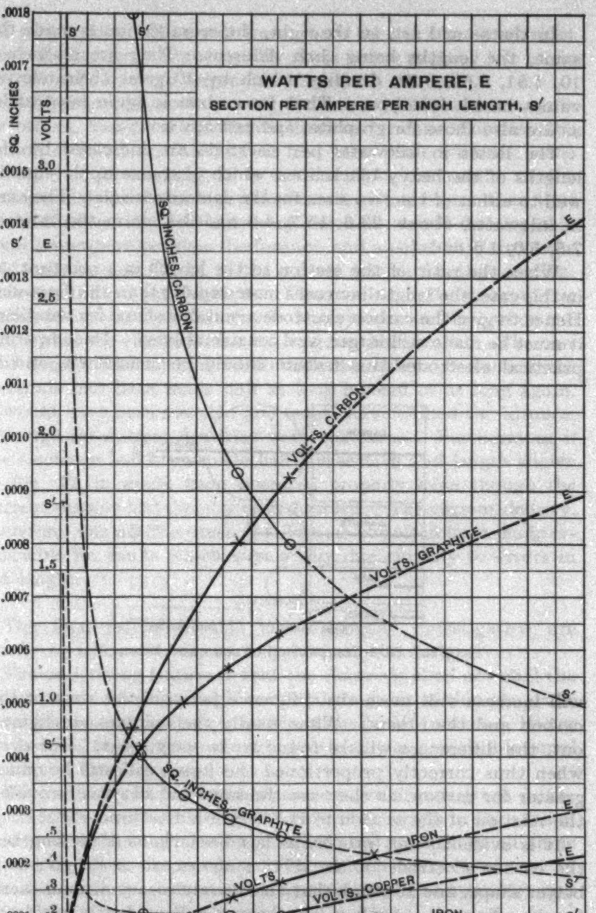

FIG. 11.—Losses and sizes; same scale

In the second set, to the right, the cross-section is made the same, the lengths being then different. They are in inches: 10, 1.51, 0.69, 0.22, dividing which by 10 gives their relative values based on copper. That for carbon is again impossible, as are also those for graphite, and perhaps iron.

The losses in kilowatts per electrode are indicated by the lengths of the heavy black lines, which of course apply equally well to either of the two sizes for the same materials. They are in kilowatts, about: 23.6, 15.2, 4.6 and 3.1, or in the ratio of 7.5, 5.0, 1.5 and 1.

When the ratio of the section to the length is a constant, as in this case, the length increases more rapidly than the diameter. Hence to give the carbon electrode a suitable shape for handling, it must be made still larger, and considerably so. In comparing practical electrodes this feature should be considered, and it will increase still more the difference between the sizes of the carbon and the others. When finally the volumes are figured out, the differences will be found to be very great. But even when thus correctly proportioned the losses will still be much greater for carbon, as they are the same for all sizes, provided the relation of the section to the length is the same.

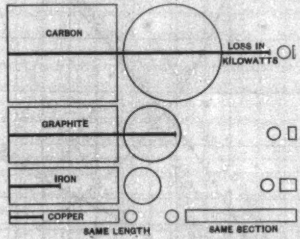

Fig. 12.—Comparison of sizes and losses

It is evidently not proper, as has been claimed, to lengthen the carbon electrode of the section shown, so as to give it a better shape, and to think that this merely means a small sacrifice in efficiency. Such a lengthening will evidently result in developing a high temperature within the walls, higher and perhaps much higher even than the furnace temperature. This would be likely to burn out the furnace wall, which would be fatal to successful operation. If it is made smaller and shorter the proportions will be still worse, as is seen in the upper right hand illustration. Consequently there seems nothing left to do but to make it much larger and longer.

This brings out another wrong deduction which has been made by others, based on the former incorrect rules. Suppose the carbon electrode in this Fig. 12 had been made with the same section but 20 in. long; it is evident from the results of the present analysis that a high temperature point, higher than that of the furnace, and probably very much so, would develop at a point somewhere between the furnace, and a point 10 in. from the cold end, because 10 in. is the correct length for that section. This would burn out the walls. The conclusion drawn from our former ideas was that the current density was too high, when the fact is that the electrode was too long for that section. The current density had nothing to do with the failure, because if the electrode had been made half as long instead of as long again, it would have been too cold and would have chilled the furnace, although the current densities were the same. Furthermore if the electrode had been made half the section and length shown in Fig. 12, it would have operated properly even though the current density had thereby been doubled. The current density, therefore, was not the cause of failure; it has often been made responsible for faults which were really due entirely to errors in the length.

SUMMARY

The final results of this rather lengthy investigation are briefly as follows, as far as they interest the designer.

The underlying feature is that the electrode shall not chill the furnace, nor develop a high temperature point within the walls at which the temperature is greater than in the furnace. Hence the hot-end temperature should be as nearly as practicable equal to that of the furnace.

The current and furnace temperature are always given in the specifications. The material and either the length or the section (but not both) may also be specified, but preferably all three should be left to the designer. The voltage and loss cannot be specified, as they are determined by the current, temperature and material.

The length (that is, the essential length, not including additions to either or both ends for other purposes than to get the energy through the walls) may be determined solely by the thickness of the furnace walls; but as this affects the cross-section, some latitude should be left in case the corresponding section is found to be too large or too small to be practicable.

The section in square inches is then determined at once by multiplying the proper temperature value of S' from Table II by the current in amperes and by the length in inches (formula 13). If this is too large or too small to be practicable, the length may be changed and the section may be re-determined. The quotient of the section divided by the length is a constant for any specified conditions, (numerically equal to S' from the table multiplied by the current) hence they may both be increased or decreased in the same proportion.

Should this table of values not be available and the specific section be known, formula (14) should be used for calculating the section. If this is also not known, then use the conductivities in formula (7). Great accuracy is not necessary when one is near the correct result, as an error in section near that point produces a relatively much smaller error in the loss.

The loss in the electrode in watts is entirely independent of the section or length adopted, provided only that their quotient is approximately as above. It is calculated in watts by multiplying the corresponding temperature value of E in Table II by the current (formula 10). If this table is not available, we may use the electrode voltage in the last part of formula (5). If this is not available either, then use the conductivities in the preceding expression of formula (5). This loss is for one electrode and it is the least possible under those conditions.

When the current for a furnace varies appreciably, the calculations must of course, be made for some assumed normal value, remembering that whenever it is less than that, the electrode will chill the furnace more or less; and whenever it is greater the electrode will get hotter within the walls, and in both cases the total loss will be greater.

In operating a furnace, if the electrode is found to chill the product, it is either too short, or too large in section. If on the other hand it is found to produce excessive temperatures within the walls, it is too long or of too small section. The current density is not a determining factor.

The hotter the outside terminal is allowed to get, the smaller the loss, but the larger the section or shorter the electrode.

When the proportions turn out to be large in section and short in length (as for instance with carbon for large currents as in Fig. 12) the relative proportions may be improved by increasing both length and section. On the other hand, if the electrode is abnormally long and small in section (as for instance with iron or copper and small currents) then if the section cannot be made smaller, there seems to be nothing left to do except to sacrifice some of the loss by making the electrode shorter and it will then chill the furnace more or less.

The additional lengths of the electrode necessary for the terminals, for feeding, or for the distribution of the current in the inside, must be calculated separately, as they are determined by entirely different laws and conditions; the above refers only to the essential part which is necessary to get the current into and out of the furnace as well as possible. The above length must therefore never include the long external part outside the furnace, for feeding purposes. Such a part radiates heat to the air and therefore follows entirely different laws of proportions. A redeeming feature of such a case is that the outside temperature used to determine the proportions of the essential part, may be allowed to be very high, probably limited chiefly by oxidation thereby reducing the total loss which has been increased by the long external part.

Summary of previous discussions. The description of this new way of attacking the problem of the proportioning of electrodes, given by the writer briefly in May, 1909, and more in detail in October 1909, has given rise to long discussions and attacks. Some of the purely technical parts were of interest and value and will be summarzied briefly below. The rest of the discussion is of no general interest as it consisted of the usual unsubstantiated claims of priority made by those who suddenly found that they had known it long ago but had not given their knowledge to others or used it themselves. It contained also the assertions of those who claimed, after the method was described, that it was obvious though this had not occurred to them before; also the statements of those who maintained that on account of some academic minutia it was obviously fundamentally incorrect, although they could not substantiate their claims with actual figures; and the assertions of others who thought that the results were of no value because the necessary physical properties of the materials were then not yet known; etc.

One of the parts of the discussions which was of value referred to the magnitude of one of the corrections to which reference was made in the original paper, due to the simplified premises. This correction referred to the effect of the variation of the conductivities with temperature, and therefore is in the nature of a refinement or second approximation. Another important part was an ingenious graphical method devised by Dr. A. E. Kennelly,* for representing and studying the relations of the quantities involved.

Concerning the temperature correction, Dr. Kennelly has shown in a very able paper† that under certain approximate premises, this correction is zero when the electrical resistivity varies according to a straight line law (the thermal one being constant). The correct mean value then is the arithmetic mean between the two extreme values at the two end temperatures. Also that the same is true when the thermal resistivity alone varies in this way. Also that when both vary in this way, the total loss is least when half of the heat flow at the cold end is joulean heat and the other half is conducted from the furnace; the remainder of the joulean heat is assumed to flow toward the furnace, thereby tending approximately to balance the furnace flow, hence a "very little heat will flow into or out of the furnace." This means that the condition of no loss of furnace heat under those approximate premises, is only a close approximation to the condition of minimum loss, instead of being identical, as it is with constant conductivities.

Dr. E. F. Roeber‡ has attempted the complicated mathematical solution of the case when both conductivities vary according to a straight line law, and has carried it up to, but not including the integration. Although this unfinished formula is probably too complicated for use in practice by engineers, it shows that for given materials at stated temperatures the correction factor is merely the numerical coefficient, and that the relations between the variable factors remain the same. Dr. Roeber also finds that when the electrical conductivity is constant and the thermal conductivity alone varies by a straight line law, this complicated formula reduces to the simple original one in the writer's paper. This indicates that it is largely the variation of the electrical conductivity which gives rise to a correction factor, a fact which the writer has since shown in another paper in a different way.

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*Trans. Am. Electrochem. Soc., Vol. 16, p. 297.

†A paper "On the Modifications in Hering's Laws of Furnace Electrodes Introduced by Including Variations in Electric and Thermal Resistivities" published elsewhere in this volume.

‡ "Electrode Losses in Electric Furnaces," Trans. Am. Electrochem. Soc. Vol. 16, p. 363. See formula (5) p. 367.

Dr. H. C. Richards* gives a very interesting solution of the integration for the complete case when both conductivities vary by straight line laws, and gives the first two terms of the series of coefficients. This enables the correction factors to be determined, when the conductivities and their variation with temperature are known. By means of this interesting solution it was shown by the writer† that even for very great variations in the conductivities, the corrections on which some of the critics based their unsubstantiated claims that the writer's approximate formulas were very incorrect and even "fundamentally wrong", were in fact quite negligible in practice.

The writer takes this opportunity to express his appreciation of these able mathematical solutions by Dr. Kennelly, Dr. Richards, and Dr. Roeber, which show that differences between the writer's simple first approximation of the complete problem and the second approximation, are not great, and in part do not exist at all. Their work was done before the present experimental determinations had been undertaken, and before some of the simplifications described in the present paper had been made.

Those who, on the other hand, attempted to belittle and discredit the results of this investigation, brought up minor points which were either based on an incomplete reading of the original paper and are answered in the present paper, or were based on academic points which it is believed the practical engineer can safely neglect or allow for, as he does in most other construction work. The present investigation was made from the standpoint of the engineer and not from that of the academician or the mathematical physicist whose enlargement of negligible minutia is apt to obscure the main practical issues; nevertheless the analytical part of this investigation is undoubtedly rigidly exact under the specified simple conditions.

It is suggested that critics who endeavor to tear down and destroy the work of others by hastily made and unsubstantiated assertions, which may prove later to have been unwarranted or incorrect, might do some thing which is really of value, by devoting their efforts to improvements and further developments instead of to mere destruction. Before tearing down a structure built by others, one should be very sure first that it is a dangerous one; if one thinks he can build a better one, then let both stand; the fittest will survive in the end without the need of the hand of the destroyer.

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* Trans. Am. Electrochem. Soc. Vol. 16, p. 304.

† *Ibid*, p. 310.

As to the usual crop of claimants of priority after something has been disclosed, the practice of secreting information of benefit to fellow engineers, until someone else has taken the trouble to publish it, and then of claiming priority and expecting recognition, is not in accordance with a high standard of professional ethics, and is believed to be more apt to discredit the claimant than to do him credit. Unpublished ideas are of no benefit to the profession at large; it is the one who takes the trouble to publish them, that aids his colleagues.

DISCUSSION ON "PROPORTIONING ELECTRODES FOR FURNACES", CHARLOTTE, N. C., MARCH 30, 1910.

A. E. Kennelly: Mr. Hering's paper is of much importance both from the practical and theoretical standpoints. In its practical aspect, it gives the results of a number of experimental observations on the behavior of electrodes under furnace conditions. It expresses the outcome of these results in tables for easy reference. The numerical bases of these tables are two experimentally determined constants for each electrode material,—the "electrode-voltage" e, and the "specific section" s. As pointed out in the paper, the "electrode-voltage" e is $\sqrt{2}$ multiplied by the square root of the ratio of the electric to the thermal resistivity; while the "specific section" is $1/\sqrt{2}$ multiplied by the geometric mean of the electric and thermal resistivities. The term "electrode-*voltage*" can only be regarded as an abbreviation for the unwieldy phrase "*voltage* drop in the electrode per square root of the temperature drop." Similarly, the term "specific *section*" can only be regarded as an abbreviation for the unwieldly phrase—"cross-*section* times square root of temperature-drop, per ampere, per unit length of electrode." It is evident that these two phrases are too cumbersome for practical use; and that brief names are necessary, even at some sacrifice in verbal precision.

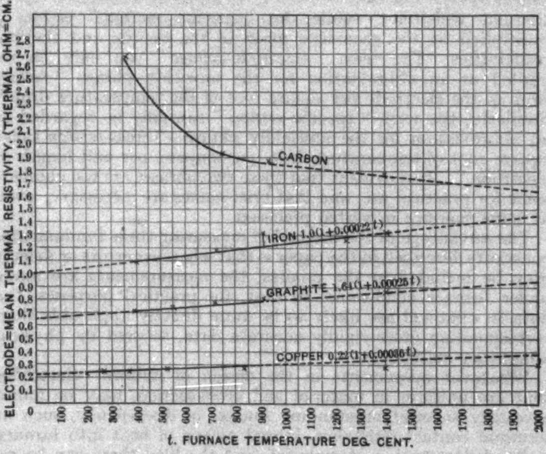
The advantage of the method of measuring these fundamental constants described in the paper is that whatever errors or defects may be included in the process, the measurements are made under furnace conditions; so that, for practical purposes, the data so obtained are likely to be more directly applicable than corresponding more rigidly accurate data, secured by physical laboratory methods.

Whatever refinements in the design of uniform electrodes that are uniform in material and cross-section, may be found necessary to meet outstanding sources of discrepancy, such as terminal contact-resistance, lateral escape of heat into furnace walls, disintegration of material, and the like, there can be no doubt that Mr. Hering's paper contains the essential engineering theory of electrode design.

It is a remarkable result of the investigation contained in the paper that copper is superior to iron, graphite, and carbon, as an electrode material, so far as concerns minimizing loss by waste of heat. One would naturally suppose at first thought, that copper would be the worst material of all for this purpose.

In its theoretical aspect, the paper also contains much that is new and valuable. Very little has hitherto been determined concerning the thermal conductivity and resistivity of electrode materials at high temperatures, so that the new data are very welcome. The values obtained are "electrode-means", as that term is defined in the paper on page 301, and are subject to the limitations involved by that definition. Nevertheless, since it has been doubtful heretofore as to whether the thermal conductivity of electrodes increased or diminished at high temperatures, these pioneer data represent a long step towards enlightenment. If even the sign of the temperature variation has been in doubt, we need not cavil at any lack of numerical precision in the newly determined thermal temperature-coefficients.

In Figs. 1, 2, 3, 4, and 8 of the paper, the electrode-mean thermal conductivities of copper, iron, graphite and carbon are plotted graphically. None of these curves carry any clear graphical self-interpretation. The corresponding numerical values of the electrode-mean thermal conductivity *k* in what may be called "thermal mhos per cm." are given in the column fifth from the end in Table I. If we plot the reciprocals of these values, or the electrode-mean thermal-resistivity in "thermal-ohm cm." as ordinates, against the furnace temperature as abscissas, we obtain the graphs of the accompanying illustration. It will be seen that the electrode-mean thermal resistivity of carbon appears to fall with temperature in much the same general manner that its electrical resistivity falls. On the other hand iron, graphite, and copper, appear from the results in the paper to follow roughly straight-line laws of increase in thermal resistivity with temperature. Their thermal resistivity follows the course of their electric resistivity in this respect. But whereas in the case of copper, for instance, the electric resistivity at



2,000 deg. cent. appears in the table as approximately nine times the electric resistivity at 0 deg. cent., the electrode-mean thermal resistivity of copper is only about 76 per cent greater at 2000 deg. cent. than at 0 deg. cent. This means probably that the inferred full thermal resistivity is about 150 per cent greater at 2000 deg. cent. than at 0 deg. cent. In other words the temperature-coefficient of increase in thermal resistivity, either in electrode-mean or in full, is apparently much less than the temperature-coefficient of electrical resistivity.

It is to be observed that whereas the electrode-mean electric resistivity of graphite, as given in Fig. 7, slightly falls off with temperature, faintly following carbon, the mean thermal resistivity steadily rises with temperature like iron and copper. This latter result is confirmed by some observations published by Mr. Hansen on page 351 of Vol. XVI of the Trans. Am. Electrochemical Society (1909) for the thermal conductivity of graphite between the limits of 37 deg. cent. and 600 deg. cent.

In the case of iron, we know that the electric resistivity undergoes marked and sudden variations in the neighborhood of the recalescent temperature, a property that is utilized in various forms of "ballast resistance." This disturbance is suggested by the bend in the curve of mean electrical resistivity for iron, on Mr. Hering's Fig. 3, in the neighborhood of 400 deg. cent. A corresponding deviation does not manifest itself in the thermal resistivity results for iron, if we exclude a particular deviation near 900 deg. cent. This is an experimental question that ought to be further investigated. If there is no discontinuity in the thermal resistivity of iron near recalescence, while there is a discontinuity in the electric resistivity, the fact has an important bearing on the theory of electric conduction in metals.

The temperature-coefficients of electrode-mean thermal resistivity in iron, graphite and copper appear from Mr. Hering's table to be respectively about 0.022, 0.025, and 0.036 per cent per degree cent. from and at 0 deg. cent. Consequently we may estimate, as a first approximation, that the full thermal-resistivity temperature-coefficient would be double the above values of 0.044, 0.05 and 0.072 respectively. This is merely equivalent to assuming that, as a first approximation the electrode-mean thermal resistivity is the arithmetical mean of the thermal resistivities at the hot and cold end of the electrode.

If my own paper, accompanying Mr. Hering's paper, had been written with these new constants available, the only alterations in the numerical examples would have been the substitution of $a = -0.0032$ for $a = -0.0072$, the distance coefficient of electric resistivity, and the substitution of $b = 0.016$ for $b = 0.01$, the distance coefficient of thermal resistivity. That is, one of these coefficients would have been reduced, and the other increased. The resulting numerical effect would have been comparatively small; but the general effect would have been to show still less deviation from the deductions of Mr. Hering's original formulas than the numerical examples actually present.

Summing up then the results of Mr. Hering's investigation from the above standpoint, we may say that with the exception of carbon, all of the materials tested showed at least substantially straight-line laws of resistivity, both electric and thermal, all the coefficients being positive, except the electric resistivity coefficient of graphite.

E. F. Northrup: Engineering problems may be classed, roughly, into those which aim to produce a material result for the first time, as building a Brooklyn bridge, and those which would repeat engineering accomplishments with better economy.

Mr. Hering's problem belongs to the latter class. He sees that there is an important engineering question to answer, which is this: How, with data which can be obtained practically, shall the material of furnace electrodes be selected; and having this, how shall it be proportioned so that, with the furnace temperatures required, the electrodes shall not chill the furnace charge while the power wasted shall be the least possible.

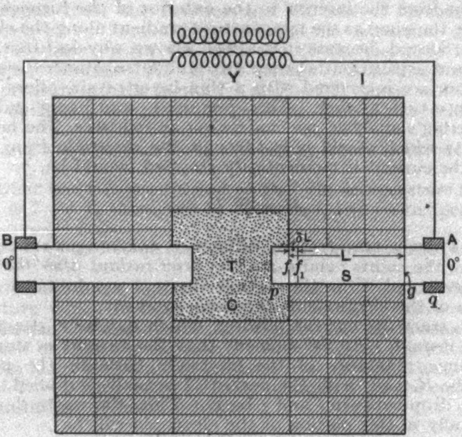
It is not a problem for elegant mathematical exposition, based upon assumptions that thermal and electric coefficients vary as idealistic functions of the temperature. It is an engineering problem and its solutions, to be of use, must have a form which designing engineers can use.

The solutions in Mr. Hering's present paper are set forth in no uncertain or vague manner and are so simple in form that a tyro may apply them in practice. Mr. Hering has introduced for the first time, the conceptions of two new specific quantities which attach to all furnace electrodes. One he calls the "electrode voltage", e, the other the "specific section", S. He points out by reference to actual experiments and theoretical considerations, how these two specific quantities may be determined precisely by experiments upon small test electrodes, and then be used for the calculation of actual large electrodes. When these specific properties of electrode materials, gotten for various furnace temperatures, are once completely determined and tabulated they will have a like value to the designer of electric furnaces that the specific heat of steam has to the designer of engine boilers.

The subject is important, much has been written upon it, and the mathematical point of view has been ably presented by several who are masters in this form of treatment. So much material has been given us that the important crucial results obtained may still remain obscure to some readers amidst the wealth of material that has been presented. These facts are made an excuse for presenting my way of looking at what appears to me the essential aspects of this interesting subject.

In the accompanying figure the two furnace electrodes A and B together with the charge, C, in the interior of the furnace complete the circuit from the transformer secondary, Y. It is assumed in what follows, that the furnace has been operated until steady conditions obtain—that is, until the heat supplied to the charge, C, equals the heat lost from the charge, so that the temperature of the central zone of the furnace charge is constant and has the required value, T degrees. It may be premised also, that the thermal conductivity of the electrodes is greater than the thermal conductivity of the furnace walls.

Now conceive that, for a brief time, the electric current is shut off. If this time, when there is no current, is taken sufficiently brief we can consider the interior of the furnace as containing an infinite quantity of heat as, compared with the small quantity which will escape in a brief interval. But in this interval some heat will flow through the furnace walls and some through the electrodes. That which goes through the electrodes, per unit of section, will exceed that which goes through the walls per unit of section, because of the assumed greater thermal conductivity of the electrode material. The heat which flows through the walls must be supplied by electric power to the charge in the interior of the furnace. To reduce this supplied power to the least possible amount involves questions which relate to the design of the containing walls of the furnace and these questions have no connection with the problem of electrode losses.



Only the heat which goes through the electrodes is an electrode loss, which it is our problem to make as small as possible. The electrode, to which the analysis should be applied, is not the physical electrode, extending from p to q (see illustration) but that portion of the electrode f to g which extends the ditance L, through the furnace wall. Of course there will be losses in the exposed portion of the electrode (which should be as short as possible) and losses in the contact resistances where the current enters; but these losses require separate consideration, and in no wise affect the problem of the choice of material and the proportioning of the electrode within the furnace wall. The electrode, then, to which this and the other treatments given should in strictness apply, is that portion which extends from the interior to the exterior surface of the furnace wall.

The treatment of the problem would be unmanageable unless it were assumed that the heat which flows through the electrode all moves parallel to its axis. This assumption is thought to be justified for any engineering requirements for two reasons; First, because, when steady conditions obtain, the temperature gradient from the interior to the exterior of the furnace wall is roughly the same as the temperature gradient along the electrode itself. Second, because it is a well known physical fact, that a surface of separation between two unlike substances, especially if the surface is covered with a thin layer of air, offers a great resistance to heat flow. This premised, and being guided by Mr. Hering's analysis, we can reason as follows. The heat-flow in watts which would pass through the electrode from f to g, when the current is momentarily stopped, would be,

$$H = K T \tag{1}$$

where T is the temperature difference taken over the length L between the points f and g *at a very brief instant after the current is stopped*, and K is the actual thermal conductance of this portion of the electrode at the same moment.

Now, start the current flowing, which has been stopped but a brief instant. At the moment that the current is started let the ohmic resistance of the electrode between the points f and g be R, and, with the current I actually supplied, let the voltage drop between f and g be E. Then the watts developed electrically in this portion of the electrode will be

$$W = \frac{E^2}{R} \tag{2}$$

This heat is assumed to escape by way of the ends of the electrode only. As its development takes place along the length of the electrode, and is distributed in some unknown manner, it will have to traverse, to escape from the ends of the electrode, a length which is less than L. Suppose when this flow of electric heat is taking place the *effective* thermal conductance of the electrode is K'. By the cooling jacket the end, g, of the electrode is supposed to be kept at the same temperature, but the heat supplied electrically will tend to modify the temperature of the hot end at a point very near this end so that the temperature at a point f_1, distance ∂L from f will become, in a brief instant after the current is started $T \pm \partial T$.

Then the electric heat which flows out of the ends of the electrode will be $K' \, (T \pm \partial T)$, and this must equal the heat supplied, if we assume that the current is maintained steady until steady conditions of temperature are acquired. Hence,

$$\frac{E^2}{R} = K' \, (T \pm \partial T) \qquad (3)$$

Now when all the heat (the current being on) which escapes from the cold end is electric heat, no heat will be escaping through the electrodes from the furnace and the loss of furnace heat will therefore be zero. Now fasten the attention on the point f_1, distant toward the cold end of the electrode from f a very small distance ∂L. If the voltage E is adjusted so that the temperature at the point f_1, is $T - \partial T$, there will be between f and f_1, a temperature gradient toward the cold end, $-\frac{\partial T}{\partial L}$, and some furnace heat will escape from the furnace. If on the other hand E is adjusted so that the temperature at the point f_1, is $T + \partial T$, there will be between f_1 and f a temperature gradient $+\frac{\partial T}{\partial L}$ and some electric heat will flow into the furnace. But this would mean that the furnace had not reached its final temperature which is contrary to the assumed condition of a steady furnace temperature, T. Hence, for no furnace heat to flow into or from the furnace, we should adjust the voltage E, until there is no temperature gradient over the small length ∂L. That is $\partial T = 0$, and we have from equation 3 for the condition of minimum loss of furnace heat,

$$E = \sqrt{R \, K'} \, \sqrt{T} \qquad (4)$$

If the product $R \, K'$ can be shown not to involve the linear dimensions of the electrode, then it is a specific property of the material of which the electrode is made. To do this write,

$$R = \frac{L}{S} \; [\rho_m]_T \text{ and } K' = \frac{S}{L} \; [\sigma_m \, a]_T$$

Then

$$R \, K' = [a \, \rho_m \, \sigma_m]_T$$

The exact interpretation of these three relations is very important. The first means that the ohmic resistance of an electrode, when hot at one end and cold at the other, will increase with its length, decrease with its cross-section, and be dependent upon the *average specific* resistance of the material which maintains when the fall of temperature from one end of the electrode to the other is T degrees, the temperature of the hot end being the same as the temperature designated by T in equation 4.

The second means, that the *effective* thermal conductance of an electrode, when heated by an electric current until the temperature of its hot end is T, and when all the heat developed must escape through the cold end, increases with its cross-section, diminishes with its length, and increases with the quantities a and σ_m. The quantity a, depends for its value upon where the center of gravity of the watts developed is located along the axis of the electrode. If this center of gravity is located at the middle point of the axis $a = 2$, if located nearer the hot end a is less than 2, if nearer the cold end a is greater than 2. K' also depends upon the mean specific conductance of the material. This is a constant for an electrode of any size and any particular material when its terminal temperatures are fixed and are produced by an electric current in the electrode. With this understood we have by substituting the value of $R\,K'$ in equation 4,

$$E = \sqrt{a\,\rho_m\,\sigma_m}\sqrt{T} = e\sqrt{T} \tag{5}$$

where $e = \sqrt{a\,\rho_m\,\sigma_m}$ is the "electrode voltage" in volts.

It should be noted here that the smaller is a, that is the nearer to the hot end is the center of gravity of the electric heat supplied to the electrode, the smaller is the electrode voltage required for minimum heat loss. In iron, a would be less than 2, in carbon, a would be greater than 2.

The minimum power consumed is

$$P_m = I\,E = I\,e\sqrt{T} \tag{6}$$

Again from (4), writing $E = I\,R$

we get $I^2 R = K'\,T$ or $I^2 \dfrac{L\,\rho_m}{S} = \dfrac{S\,a\,\sigma_m}{L}\,T$,

which gives

$$S = I\,L\sqrt{\frac{\rho_m}{a\,\sigma_m}}\cdot\frac{1}{\sqrt{T}} = I\,L\,s\,\frac{1}{\sqrt{T}} \tag{7}$$

Equation (7) is the same as Mr. Hering's equation (7) p. 295, except that the quantity a replaces the factor 2. a will equal 2 only when the center of gravity of the watts supplied to the electrode is at the middle point of the axis and there is no furnace heat flowing. This will be the case generally only when the thermal conductivity and the electric resistivity are constants.

The quantity $s = \sqrt{\left[\frac{\rho_m}{a\ \sigma_m}\right]_T}$ is what Mr. Hering calls the "specific cross-section". It is independent of the linear dimensions of the electrode but is dependent upon its material and upon the terminal temperatures being assigned at the time its value is determined. Its value will also be different if determined in any non-electrical way other than by the method described by Mr. Hering.

The two equations of Mr. Hering (modified here by substituting a for the factor 2).

$$P_m = I \sqrt{a\, \rho_m\, \sigma_m} \sqrt{T} = I\, e \sqrt{T} \tag{8}$$

and

$$S = I\, L \sqrt{\frac{\rho_m}{a\ \sigma_m}} \cdot \frac{1}{\sqrt{T}} = I\, L\, s\, \frac{1}{\sqrt{T}} \tag{9}$$

the first of which enables the minimum power loss to be calculated and the second the proper electrode section for minimum power loss, I conceive to be the most important theoretical contribution to this subject.

Equations (8) and (9) would be useless if the quantities e and S could not be obtained by experiment. But fortunately, Mr. Hering has pointed out, and demonstrated by actual tests, that they can be so obtained, *and with far more ease and precision* than their components thermal conductivity, electrical resistivity and the center of gravity factor.

The analytical and mathematical treatments, that others have given to this problem, are certainly interesting and valuable in enabling the problem to be studied from very varied points of view. But the following aspects of these mathematical modes of treatment certainly should not go unmentioned. If the thermal and electric conductivities are assumed constant, then the most elemental physical considerations will lead to a solution without any application of the calculus. Such solution, however, is only roughly approximate. If these quantities are assumed to vary as a linear function of the distance along the electrode, then the solution of the differential equation, based upon this assumption, shows that the temperature gradient is not linear and hence the original assumption can only roughly represent the physical facts—probably no more closely than the assumption of constant specific qualities. If the conductivities are assumed to vary as linear or more complicated functions of the temperature, the integrations are at best formidable and generally impossible. An unintegrated differential equation is at the best nothing more than a formal statement, put into mathematical form, of an unsolved problem.

Respecting this view of the mathematical analysis of physical problems Fourier remarks, (§13, The Analytical Theory of Heat), " The numerical interpretation of the results of analysis is necessary, and it is a degree of perfection which it would be very important to give to every application of analysis to the natural sciences. So long as it is not obtained, the solutions may be said to remain incomplete and useless, and the truth which it is proposed to discover is no less hidden in the formulae of analysis than it was in the physical problem itself."

But suppose one does succeed in writing down and integrating the differential equations which express the conditions of the flow of heat in an electrode. These equations must involve the thermal conductivity varying as a function of the temperature. To obtain, then from the integrated equations numerical results one must know the thermal conductivity of such materials as carbon, graphite, iron, etc., at temperatures from, say, 100 to 2000 deg. cent. These variable " constants " are unknown and to determine them by experiment is *a far more difficult and uncertain undertaking* than it is to measure directly at various temperatures what we want to know; namely, Mr. Hering's electrode voltage, e, and specific section s.

It seems to me that there lies here an important line of investigation, which shall give us the values of e and s, at temperatures up to the highest employed in electric furnaces of all the electrode materials which are likely to be used in these furnaces. Mr. Hering worked with thermo couples to measure his temperatures and did not get up very high. His experimental investigation should be continued, using test pieces of greater ratio of diameter to length, larger currents and higher temperatures than he used. These high temperatures might be quite accurately measured by placing reliance on Steffan's law, that the total radiation from a black body is proportional to the fourth power of the absolute temperature. The radiation could be measured with a form of surface bolometer which the writer has designed and experimented with. This, after being calibrated at moderate temperatures with a thermo couple, could be relied upon to give accurate results at the highest temperatures. A series of values $E = e\sqrt{T}$ and $S' = s\frac{1}{\sqrt{T}}$ could be found thus and tabulated for temperatures exceeding 1500 deg. cent. These constants given by Mr. Hering in table II page 322, are exterpolated values above 950 deg. cent. This was the highest actual steady temperature which he measured, but a platinum-platinum rhodium couple used in connection with a potentiometer could have been used without its destruction to 1500 deg. cent. Beyond this temperature the radiation principle would have to be used, and the results which it would give would be as accurate as the higher temperatures of the furnaces are known, as these can only be determined in the same way.

The writer hopes that this more extended investigation may be deemed worth while and he would give it as his opinion, based upon considerable experience in making high temperature determinations, that results of an accuracy entirely satisfactory from an engineering standpoint could be readily obtained in the ways suggested. Such an investigation might be carried out with much propriety at the National Bureau of Standards.

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PARALLEL OPERATION OF HYDROELECTRIC PLANTS

BY W. S. LEE

It is the purpose of this paper to sum up in a general way some of the advantages to be gained by operating a sytem of hydroelectric plants connected in parallel so as to exchange power from one plant or territory to another. The disadvantages of this system, which are almost all transmission operating conditions, have been purposely omitted, in the hope that some member may at a future meeting treat this phase of the subject, giving a solution of the problems involved. The deductions, although drawn from conditions existing on the southern Appalachian slopes, will in most cases apply to other localities.

It seems best to first consider some of the topographical features of this locality. The Appalachian mountains, in which many large streams have their sources, run in a southwesterly direction, paralleling the Atlantic coast. These mountains are, on an average, from 1500 to 2000 feet above the sea level. This means that all water from their water sheds must run over falls or rapids dropping a total vertical distance corresponding to this height. In the higher altitudes there are numerous waterfalls with an abrupt drop of many feet, but as lower levels are reached the falls consist mostly of rapids, some grouped so as to present considerable fall in a short distance, and in other places a longer and more gradual slope.

Several well-defined ridges cross the various streams running parallel to the Atlantic slope, on which each river has a decided fall. These ridges extend across two or more states and several streams. These points on the streams present the largest and most economical sites for hydroelectric developments. Near these falls, or between them, are others of a gentler slope which are much more costly to develop.

Each stream has available a certain amount of water power and the problem is to build and operate plants on the same and on different streams, interconnecting them with transmission lines, so that the greatest amount of power can be delivered from all the streams.

For convenience, we will consider the advantages to be gained by parallel operation under the following heads:

More than one plant located on the same stream.
Plants located on different streams.
Effect of low water on a system of plants.
Effect of high water on a system of plants.
Storage.
Break-down capacity.
Auxiliary plants.
Variation of load.
Constructing and operating advantages.

More than One Plant Located on the Same Stream. Rainfall and floods are features that should be carefully considered in connection with hydroelectric plants especially when operated in parallel. To illustrate this point some tabulated data are given regarding rainfall from the year 1900 to 1909 at the stations located at Morganton, N. C., Statesville, N. C., Charlotte, N. C. and Camden, S. C., all forming part of the drainage area of the Catawba river.

It will be seen by referring to this table that in several instances one point may have an excess of rainfall and another have a deficiency, or vice versa.

After the plants are built comes the consideration of their operation during various stages of water. The two stages which interfere with operation are extreme low water and extreme high water. While low water generally extends over the whole country it is very unusual that there are not some places where the streams furnish more water than others, due to variation in rainfall or to climatic conditions. These places may not necessarily be in the same section each year, and the areas of increased or decreased rainfall may shift and vary from year to year.

Low water means a curtailment of power, and it is often found that even with a line of plants located on the same stream the water conditions are different at different plants. There may be

AVERAGE RAINFALL

Year	MORGANTOWN, N. C.				STATESVILLE, N. C.				CHARLOTTE, N. C.				CAMDEN. S. C.			
	Av. precip. for prev. years	Annual precipit.	Excess	Defic.	Av. precip. for prev. years	Annual precipit.	Excess	Defic.	Av. precip. for prev. years	Annual precipit.	Excess	Defic.	Av. precip. for prev. years	Annual precipit.	Excess	Defic.
1900	*11* 47.93	46.68	—	1.25	*6* 53.01	No. Record	—	—	*21* 49.64	46.34	—	3.30	*10* 47.15	51.79	4.64	—
1901	*12* 47.83	63.19	15.36	—	*6* 53.01	62.84	9.83	—	*22* 49.49	62.82	13.33	—	*11* 47.57	58.64	11.07	—
1902	*13* 49.01	44.77	—	4.24	*7* 54.41	48.35	—	6.06	*23* 50.07	45.32	—	4.75	*12* 48.49	45.17	—	3.32
1903	*14* 48.70	52.04	3.34	—	*8* 53.66	53.64	—	0.02	*24* 49.87	39.48	—	10.39	*13* 48.24	55.06	6.82	—
1904	*15* 48.93	42.31	—	6.62	*9* 53.65	36.70	—	16.95	*25* 49.45	41.93	—	7.52	*14* 48.72	37.90	—	10.82
1905	*16* 48.51	57.04	8.53	—	*10* 51.96	49.91	—	2.05	*26* 49.17	42.44	—	6.73	*15* 48.00	42.41	—	5.59
1096	*17* 49.02	57.86	8.84	—	*11* 51.77	50.82	—	0.95	*27* 48.92	47.30	—	1.62	*16* 47.65	51.17	3.52	—
1907	*18* 49.51	47.94	—	1.57	*12* 51.69	39.46	—	12.23	*28* 48.86	39.98	—	8.88	*17* 47.86	45.61	—	2.25
1908	*19* 49.42	66.44	17.02	—	*13* 50.75	Partial Record	—	—	*29* 48.55	54.40	5.85	—	*18* 47.74	51.15*	4.41	—
1909	*20* 50.27	No Record	—	—	—	—	—	—	*30* 48.75	No Record	—	—	*19* 47.97	No Record	—	—

* Mean of 2 observations.

NOTE.—Records of missing months have been interpolated by using corresponding records of adjacent rainfall stations. Italic figures in columns for average precipitation denote the number of previous years.

local rains that benefit one plant one day and do not benefit plants at some distance for two or three days thereafter.

In case of operating under flood conditions the reverse is true, namely; a flood may affect a plant on the upper part of the river and not affect a plant lower down for several days. In the meantime the water has become normal at the upper plant and no longer interferes with its power output or the proper speed of the wheels.

On a system where several plants are located on the same stream, the head operator has many problems which can be solved to the company's advantage by passing water from one reservoir to another, so as to produce the greatest kilowatt-hour output from the combined plants.

Plants Located on Different Streams. It will be readily observed that many of the same conditions and advantages that apply to several plants located on the same stream, apply to plants located on different streams. There are, however, some features in connection with low water and floods which should be considered. The question of low water can be handled much more advantageously when plants are located on different streams as it is rarely the case that areas of abnormal rainfall extend over different valleys and different parts of them to the same extent. The rainfall may vary a great deal even in the same valley, but this variation is always more pronounced in different valleys. Just as the effects of low water are minimized by having plants on different streams, so are the effects of high water. The floods that interfere with the operation of plants are the large ones, and it is a very rare occurrence to have a large flood on two different streams at the same time.

Effect of Low Water on a System of Plants. The low-water flow of any stream or streams in connection with a hydroelectric system operated in parallel, determines the value of the system. In the operation of plants located many miles apart not only can advantage be taken of variation of rainfall in different parts of the various drainage areas, but it is found possible to regulate the flow of water from plant to plant on the streams so as to produce the greatest power output.

In operating such a system of plants on the load in this territory, we are often enabled to lower the ponds or storage capacity towards the end of the week, refilling them on Sundays.

If an operating man has only one plant he dares not take any chances by lowering the water in the pond to too great an extent, the result being that he does not get the amount of power from the plant that he would if it operated in parallel with other plants.

As to just what this increased value of power output is cannot be determined except for fixed systems, but for any system in which there are as many as three plants, well located, it is safe to say that the low-water output can be increased at least 15 per cent.

Effect of High Water on a System of Plants. In the case of low-head plants, high water affects them very materially owing to the fact that the decrease from normal head is a large proportion of total head. On the other hand, the higher head plants are not affected so much. It very rarely occurs that all plants in a system are of the same head; consequently, the system would have an operating advantage in time of high water due to this reason. Also, in considering the flood action on a system of plants on the same stream, we must investigate the velocity of such a flood. There may be heavy rains in one part of the valley causing an excessive local flood that will not affect a plant located thirty miles or more below, and the upper plant can be put back into commission before the flood will affect the plant lower down, and so on.

Storage. It is evidently advantageous to have a chain or system of plants in connection with the storage of water. When the plants are connected together in parallel it matters not what size reservoir each particular plant may have, as all the water can be made available by the operator as if it were in one large reservoir. This, of course, will make it necessary for the operator to draw continuously on plants that have small reservoirs, using the plants with large reservoirs in cases of emergency or heavy peak loads.

Excess or Peak Load Capacity. In every plant it is necessary to have an overload or peak load installation, as no power service has a steady load at all times. In the construction of hydroelectric plants it is always found advisable to install some additional equipment for this purpose. The percentage of this excess capacity is necessarily greater in an isolated plant than it would be where several plants are connected together in parallel. In cases where several plants are operated in parallel the excess capacity can often times be installed in plants nearer the load, or in a more desirable place for operation, than would be possible if each plant had to carry its proportionate amount of reserve capacity.

Breakdown Capacity. It is well known to all operators that interruptions to some plant are liable to occur from time to time, due to breakdown or some defect which may develop. It can readily be seen that with a chain of plants an interruption at one plant would not be serious, as other plants on the system could be called on for overload or excess load during such an interruption. It often happens that some breakdown in one plant could be repaired much quicker if the whole power house could be shut down.

Auxiliary Plants. Due to the extreme variation of high and low water, one of the problems in hydroelectric development is to be able to get as much power as possible from a variable stream. If a plant is based and built on extreme low water, there is from six to twelve months in the year, varying of course with the rainfall, a great amount of surplus power. It becomes very desirable to make installations that will take care of as much of this flowage as it is profitable to sell. These variations are so erratic that they cannot be even approximately determined, and it is therefore necessary to install some auxiliary plants. When plants are operated singly it is generally necessary to place an auxiliary steam plant at the water power plant, and as water powers are generally in some out of the way place, the cost of construction and operation of the auxiliary is high. But where a system of plants is operated in parallel the problem of auxiliary plants is very much simplified. Plants may be located so as to take care of territories at the ends of transmission lines; or they may be in the midst of the largest power districts, thereby reducing the line loss; or they may be placed at a point where low freight rates on fuel prevail.

Variation of Load. The ideal load for any power system is one made up of a great number of different kinds of customers. The greater the territory over which any system operates, necessarily the greater the diversity of manufactures, and the nearer do we approach ideal conditions. The largest part of the load in this particular section consists of cotton mills, and although this is supposed to be a ten-hour constant load there is a variation on our different lines from week to week, due to the market demand for different classes of goods. To cite a particular case; a number of mills in one locality spinning coarse yarn may be shut down in the middle of the week, while the mills in another district, spinning fine yarns, may be running overtime, due to the demand for these particular goods; consequently, a system of plants will have a much better load factor than would be possible with singly operated plants.

Constructing and Operating Advantages. Another great advantage to the construction engineer while building on a stream on which some other plant is operated above him, is the ability to regulate the flow of the river while putting in coffer dams or difficult parts of the foundation. This, of course, would only apply to a plant located below one in operation, but it can be used many times during course of construction.

The advantages of operating a large transmission system are many and easily understood by the practical operating man. The operating manager is able to handle the system from one point to much better advantage than if it had to be operated from different points. He has a better opportunity of training his operating forces, as the men can be promoted from one department to another as they become proficient and familiar with the system.

We next come to the question of cost of attendance for a system of plants. The load in this particular territory is such that it does not require all of the plants to be in operation more than twelve hours a day. This enables the company to so man the stations that twenty-four hour shifts are not necessary in all plants.

ONE TRANSMISSION SYSTEM WHERE POSSIBLE

In the Piedmont section are many small growing towns scattered several miles apart and vying with each other in manufacturing. As there is a large territory to cover its calls for a high tension *distributing* rather than a high tension *transmission* company.

If parallel operation of generating plants is economical, desirable, and capable of better service to customers, why is not one transmission system best to serve a large territory? Let us consider the following problems in regard to the transmission system:

Ability to furnish better service.
Cost of transmission system.
Serving one or more generating companies.
Construction and operation.

Ability to Furnish Better Service. The matter of first consideration to the hydroelectrical engineer of any system, great or small, is reliability of service. If there are advantages in operating generating plants in parallel there must be still greater advantages in supplying customers from one general transmission system. The large transmission system presents many possibilities for belt lines and tie-in lines, which strengthen the service and which would not be possible on a small isolated system. Duplicate lines can be so laid out that while they are not built close together they eventually reach the same point. By this plan they reach and serve separate territories and come together at a fixed point, there furnishing duplicate service. In case of interruption to one line, power can often be furnished from another direction until necessary repairs can be made.

Cost of Transmission System. In the construction of a large distributing system the lines will probably cost more at first than those of the smaller system. As the country develops and the load increases, the relative cost will be reduced, so that the final cost will be less per kilowatt than for several small systems. There will be an increased cost, due to many switching and tie-in stations, but this, I believe, will be offset by being able to work the lines up to their full capacity. The larger systems will only add additional lines as the load increases to warrant their construction, while, on the other hand, it would be almost impossible to lay out the small system so as to use all the copper in the lines to best advantage.

Serving One or More Generating Companies. When a large transmission system is laid out to serve power consumers to the best advantage, it is an easy matter to tap the system and take on additional power from any new generating station.

The operation of a hydroelectric system resolves itself into three parts; generation, transmission and distribution. Any part is susceptible of being segregated so as to determine its pro rata cost or profit. This being the case, it will readily be seen that a large transmission system will furnish to the prospective builder of a generating plant a better market for the sale of his output than he would have if he determined to enter all three fields. It will make no difference to the distributing system whether the generating plants are owned by the same company or by different companies.

Constructing and Operating Advantages. Owing to the fact that most water power sites are in almost inaccessible places, the question of power for use during construction should be considered. If the plant is built with a view to operating in parallel with some other plant it is merely a question of building the transmission lines at first and using power from the completed plants for constructing the new ones. This has been worked out in actual practice and is found very desirable.

CONCLUSION

The advantages enumerated above which are claimed for plants operating in parallel are in the ultimate, economic ones, and this paper does not seem complete without some reference to the general conditions surrounding the water power situation at the present time.

We have already referred to the benefits to be derived from the proper location of the various dams on a stream, but even at this early stage of the hydroelectric art we find it necessary to consider conditions already existing. In many places we find the power of water falls has been partially utilized in a manner which makes complete development of their power almost impossible without destroying existing developments. We also find in many places a little fall above and below sites for development, covering several miles of river front, which is difficult to include. The development is often made to include only the main fall on account of the difficulty of acquiring the riparian rights for the total fall. Again, other obstacles are often encountered, such as highways or railroads which interfere with complete development, and a partial development is made without removing these obstacles which could often be done to the satisfaction of everyone. This is a very poor policy and is equivalent to wasting that much of available power.

Furthermore, almost every undeveloped water power is in some remote place difficult of access. This makes it necessary to provide some means of transportation for machinery and materials during construction. This item of transportation is a large part of the cost of development, especially when the plant is a small one. For this reason, if for no other, each of these developments should be considered very carefully with the idea of developing as large a power as possible, even if it is necessary to spend some time in getting additional water and flowage rights.

And here let me advocate the passage of liberal condemnation laws, so that anyone actually desiring to develop a water power could do so without being blocked by minor or unimportant interests, for up to the present time it has been found that one of the most difficult matters in connection with hydroelectric development is the acquisition of land and riparian rights.

This item represents about 10 per cent of the cost of development. Several of the states have passed condemnation laws, and other states, which have no general law, often give special charters allowing condemnation. While there is a tendency on the part of many people to object to this policy, it should be continued.

It is a well established fact that the growth of the country around a development is very rapid, increasing the taxable values not only by the amount invested in the development but also by the investment in manufacturing interests which follow them.

I know of no business in which as much money has been invested as in hydroelectric developments that has made such a poor return on the investment. Seventy-five per cent of the reports made on proposed hydroelectric developments are jokes. Moreover, the local papers, when a development is proposed or started, are eager to magnify the amount of power, the cost of construction and the value of the investment. The result is that the entire country has been trained to believe in a general condition that does not exist. Promoters have taken advantage of this condition, and many plants have been built or started that have proved failures.

The investigation of a proposed hydroelectric development requires a great deal of work and study by trained and experienced men, as there are more varying features entering into consideration than in any other branch of engineering. Most reports are made hurriedly without proper investigation, hence disappointment follows. The engineers who make these reports are not wholly to blame, for they are seldom allowed the necessary time or facilities to make proper investigation on account of the cost involved.

The standard for determining the cost of power to-day is based upon the cost of power produced from coal. As the supply of coal is consumed the cost of power will necessarily increase and a new standard of cost will be established. Any tendency to block or interefere with the development of water power is necessarily forcing the consumption of coal and hastening the day when the price of power must increase according to the law of supply and demand. I fear that many of our conservation advocates who are endeavoring to prevent the destruction of our natural resources are really hastening it.

We are all aware that our Government, which should publish carefully and accurately prepared reports, is contributing an influence which is not favorable to the early development of our water powers. Some laws have been passed, and still many more proposed, with apparently no other object than to stop further development. The public which has been taught that the investor is getting more than he should, endeavors to block development in every conceivable way. The result of these conditions is that the investor has been sorely disappointed and is ceasing to invest. In the meanwhile, a latent or dormant energy is running to waste, and we are consuming a limited coal supply which should be preserved.

The engineering profession should study these conditions carefully and exert every influence to place this matter before our Government and the public in its true color; thus only can we hope to utilize in the immediate future the vast resources of our streams with the greatest possible economy.

To my mind *true conservation* does not consist in postponing the utilization of power now going to waste, and which can never be regained, but rather in utilizing these resources at present that cannot be kept for use at a future time.

DISCUSSION ON "PARALLEL OPERATION OF HYDROELECTRIC PLANTS." CHARLOTTE, N. C., MARCH 31, 1910.

W. S. Lee: In describing some of the features that enter into the design, construction and operation of our plants here I have endeavored to present them in a general way—in a way which should be considered by every engineer who contemplates a large development consisting of a chain of power plants.

The questions that arise in this kind of work are not always strictly engineering problems. There are commercial and political questions. The problems encountered in this particular section were, principally, a great variation in flow, a scattered market, and a market for power that is used only for a comparatively short portion of the day. I believe that it will not pay to develop an isolated plant in this country, considering the rates at which we have to sell power and the distances over which we have to transmit the power, unless it is a very large one. It is true we have many small powers that can be developed and utilized close by, in cotton mills, many of which have their own plants, but when the transmission field is entered it will not pay to handle these small plants.

While these questions may not be purely engineering problems, they are problems which the engineers of the country must help solve. There is no question that whoever has to operate an isolated plant, with a variable stream, is not going to get power from that plant with the same confidence that he would if he had other plants which he could call upon, or some reserve power. We find that condition in actual experience. With due respect for my own operating department here, I find that it frequently saves the water, fearing that there will not be enough to last through the week, and as a result the water is wasted.

Chas. E. Waddell: I think Mr. Lee has well treated the subject of the economics of parallel operation of plants from the standpoint of the southern engineer, and he has equally well dwelt on the attitude of the public towards these developments. I think he is conservative in estimating the advantages of the investment have been as 5 to 1 wherever a large undertaking of this kind has been made in the South in the increased value of manufacturing sites, manufacturing itself, and of real estate in the vicinity, and I think he might well have added to the paper a corollary on the advantages of such a system to the consumer. Briefly stated these advantages are:

1. With a distribution system such as this, and the use of three transformers connected in delta, a customer has practically a duplicate plant at the cost of one; for, should a line go down or one transformer be destroyed, operation is still possible.

2. The inertia of the large system, once running, is so great that throwing on or off large induction motors does not materially affect frequency or power factor.

3. Uniformity of rates for installations of equal characteristics places all manufacturers on an equal footing, and if competition exists it must be based on factors of cost other than power.

4. The coöperation between a customer and the engineering department of the large hydroelectric companies insures the customer of engineering advice of a much higher order than a small manufacturer would ordinarily have at his disposal.

All of us will heartily agree with Mr. Lee in what he says about educating the public to the great advantages of these systems, and the necessity of passing laws that are equitable and fair and particularly to give the hydroelectric companies greater latitude in the matter of condemnation processes and the right of eminent domain. If I mistake not, it is a law in this state at the present time that power companies have the right of eminent domain for transmission lines. The legislators and the public at large already begin to recognize these interests are public utilities, and should be given powers that are ordinarily delegated to railroads and corporations of that nature. I think it is manifestly fair and right, and I think it is our duty as engineers—because we know both the public's side and the company's side of these questions—to educate the public with which we come in contact to realize the advantages of the universal development of our water resources, their harmonious operation to the advantage of all interests, to recognize the advantage of equality in the rates, and not block development by unjust or antiquated laws that apply to a former age and have no place in the century in which we now live.

Percy H. Thomas: I would like to ask Mr. Lee how the speeds of the various water wheels in the system is maintained, and incidentally, what provision is made for voltage adjustment. And a second question is as to operation—whether all lines of the same voltage are tied together and so protected that any line breaking down will be automatically cut out; or whether the plant and substations are operated in sections, so that if anything happens to one section the lines on this section can be thrown over to another section; or whether separate sections are maintained, the different sections being tied together by instantaneous circuit-breakers? These are three possible ways of operating such a system, and Mr. Lee's experience would be very valuable.

It is interesting to note to what a high voltage this plant is now carried, even though the distances to which power is being transmitted would possibly not demand so great a pressure. I believe it is a very wise arrangement; not only does it give greater efficiency and splendid regulation of voltage, but it provides a large amount of changing current which will tend to neutralize the effect of the inductance of the induction motors, and further will permit a temporary transmission of power through roundabout circuits in case of injury to some main line. Two or three times the normal distance might be traveled, under such circumstances, without causing any particular disturbance of voltage of serious transmission losses.

There is another side to the problem which Mr. Lee has presented, and which he has of course fully considered—how far is it possible to build up a load whose load curve shall follow that of the water power available. It is, of course, desirable to utilize storage to permit the use of every possible kilowatt-hour from the river, but it is also worth while to encourage the sort of load which follows as far as possible the power available. Possibly Mr. Lee would give us a few remarks on the limitations in the control of the load curve—these limitations, of course, are very great.

What is wanted is some way of using overflow power; as for metallurgical or electrochemical work, or some other way. The ideal arrangement would be some process which can be carried on at night, and which does not require a heavy plant investment; giving some product which has a good steady market value and which is easily shipped. For example, if some fertilizer could be manufactured at night with the overflow current, and shipped in carload lots to the country hereabout, it would be a very great advantage to the power system. Apparently, at the present time there is no such use for overflow power which is really practicable and available. It would seem almost certain, however, that in the future there will be found something which will be more satisfactory.

Considering Mr. Lee's discussion of the advantages of multiple power stations, not only do we gain from having a large number of hydroelectric plants in the same system, but we will gain, as the author has brought out, by having them widely distributed not only three consecutive power houses on one river, but having the power stations on opposite sides of the distribution area allowing the source of power for any particular load to be chosen at will.

Mr. Lee has spoken of the advantage in looking ahead in laying out a large power system. There can certainly be no question about the wisdom of that principle. I think it is also true that every big power system, like every other large undertaking, is an evolution, and must have its growth guided by its past experience; and if we start with a central idea which appears best at the time, it is not wise to determine conditions too far ahead, because conditions are likely to change, and it will be better to have the development flexible enough to take advantage of the situation existing at the time of action.

D. B. Rushmore: A feature of Mr. Lee's paper deserving of particular discussion is the use of steam auxiliary plants in connection with large hydroelectric systems where the power stations are developed to a point above the minimum flow of the streams. In a few localities, such as Niagara Falls, steam auxiliary plants are needed only as an insurance against breakdown of transmission lines. Such plants may, however, perform various functions, such as taking the peak loads, of supplying the wattless current of the system, etc. At the present time the development of a hydroelectric system necessarily involves the use of such steam auxiliaries.

A. M. Schoen: The points of advantage to be derived from the parallel operation of hydroelectric plants, as explained by Mr. Lee in his very able paper, are too self-evident to need discussion, but if these advantages accrue from tying together a single group of plants in a fairly circumscribed area it would seem that the extension of the same system over a wide area would accomplish results even more to be desired. One of the principal factors justifying the arrangement recommended by Mr. Lee is the fact that if, with several plants so grouped together, each stream takes its water from a different drainage area, there will be a greater tendency towards flattening out the primary power curve, thus increasing the salable primary power against the corresponding decrease in the secondary, as extreme low water in two well separated basins at the same time is unlikely, and this improbability continues to increase with the number of streams drawn upon and the increased separation of their drainage basins.

Take, for instance, one of the southern counties, the commissioners for which recently requested me to formulate specifications under which four competing hydroelectric power companies should be permitted to run their transmission and distribution systems. Two of the companies were located at adjacent points, on the same river, while the other two were supplied from entirely different streams, taking their rise and supplementary supplies hundreds of miles from each other and from the first river. Any arrangements between these four companies by which they might supplement each others' power in extreme cases would seem to be mutually beneficial, as such an arrangement would result in increasing the salable primary power to a greater or less extent for all four without calling for additional equipment, except in the pole lines, assuming, of course, that all were using the same voltage, periodicity and frequency. This serves to accentuate the particular point I had in mind when rising to discuss Mr. Lee's paper, namely, the need for conforming to some general standard when installing plants of this kind, for in my opinion, the time is coming when there will be some general working arrangement, even if the ownership is different, between plants of this character operated in the same section of the country. Indeed, it is hardly too great a stretch of the imagination to say that the time may come when sections rich in water power, such as the Piedmont section of the southern Appalachians, will be covered by transmission lines fed at intervals from the various power houses, thus creating one large interdependent system furnishing a maximum primary power supply to the country within reach, and under the most advantageous conditions both to operator and consumer; and should this occur, the next step in natural sequence when such relationship between the properties existed would seem to be an arrangement of dams across streams at judiciously selected points between the mountains, resulting in the impounding of these waters by means of artificial lakes and a consequent increase in the water stage of the streams affected with corresponding increase in primary power.

Carl Hering: Regarding the utilization of electric power from hydroelectric plants at such times during the day, night or year when there is plenty of water and a light load, there is probably no better way to utilize that power than for some electrochemical or furnace processes which can be started and stopped at prearranged times, and which require large amounts of power but must get this power very cheaply in order to make the processes commercial.

It seems to me that this has not been given the attention which it deserves. Such power could be delivered very cheaply, yet with great profit, as the cost of it to the producer is extremely small because this cost should be charged with only the difference between the cost of operating with and without this extra load. If power at such low costs were offered at prices agreed upon for reasonably long terms, it would probably find a sale when the offer became generally known.

Even a furnace might be operated during a limited period every day, if enough current could be obtained during the rest of the day to merely keep it hot; and when furnaces are designed and proportioned more carefully to reduce the heat losses, as they undoubtedly will be after it becomes known how to design them properly, these stand-by losses ought to be reasonably small. A case has been reported in which this was profitable even when coal was the fuel, and it would therefore be much more so when the source is an excess of water, and when it becomes possible to design the furnaces more correctly.

H. N. Muller: It might be of interest to the people here to know that power is now being used in the off peak periods in the Pittsburgh district for the manufacture of steel, or rather the refining of steel that has been preheated and somewhat refined in the open hearth furnace, or made from the scrap, at a cost of about one cent per kilowatt-hour for current. This has been carried on for over a year, and while I do not know what the manufacturers' profit has been on this steel, which is used principally for high grade tool steel, they are still completely equipped with crucibles, and I feel they would revert to the former methods if the electric furnace was not more profitable.

W. L. Waters: Mr. Lee's paper deals in a complete, though brief, manner with the fundamental engineering and economic questions connected with hydroelectric power distribution. The only suggestion I wish to make on this subject is that the induction type of generator should be considered more frequently for such installations. The disadvantage of operating a large number of small power stations, is the increased expense due to the attendance required for each station. In large city power stations it has been found more economical and advisable to operate power stations of 100,000 to 200,000 kw. capacity, when the conditions in regard to the magnitude and location of load justifies such a size. In a well distributed water power system such as Mr. Lee has referred to a power station of this capacity is usually impossible as the water power is not located at one point.

The induction generator consists of an induction motor operated above synchronous speed, and the advantage of this type of machine is simplicity of construction and operation. The induction generator does not require any direct current exciting system or complicated switching gear. In addition there are no governor or parallel-operation troubles and the units once put on the line can take care of themselves, the load being regulated by the governor of the prime mover. The objection to induction generators is that they require a wattless magnetizing current which must be supplied by the system. Just as an induction motor takes a wattless magnetizing current from the line and delivers mechanical power, so the induction generator takes wattless magnetizing current from the system while it supplies the watt component of the whole.

Two years ago I presented to the Institute a paper on the induction generator as applied to large power station work. In this paper I dealt mainly with the application of this type of generator to large power stations operating a considerable amount of synchronous apparatus, and the question of such units in connection with large water power systems was only briefly touched on; the reason for this being that there was practically no large overhead transmission system operating with the high voltage at which the Southern Power Company is operating at the present time. The possibility of operating large overhead systems at 100,000 volts changes the situation completely. Mr. Fraser states that the capacity charging current for 140 miles of the Southern Power Company's 100,000 volt line is about 7,000 kilovolt-amperes. These 7,000 kilovolt-amperes will supply the full load wattless magnetizing current for 20,000 to 30,000 kw. of steam-turbine-driven induction generators or about one-half that capacity of waterwheel-driven units. Mr. Lee will tell us the Southern Power Company expects within the next five years to have the 100,000 volt line so extended that the charging current will probably be increased to 20,000 kilovolt-amperes. If this is the case the overhead system would be capable of supplying the full load wattless magnetizing current for from 30,000 to 100,000 kw. of induction generators, the exact capacity depending upon the speed and the voltage at which they are operated.

The commercial history of the induction generator has been comparatively brief. The first application of any size was a

1200-kw. unit installed in the Baltimore Copper and Smelting Rolling Company's plant about six years ago, while recently three larger units have been installed in the Interborough Rapid Transit Company's power station in New York City. The generators in both of these installations supply power to rotary converters which transform the alternating current to direct current. The induction generator appears to have been somewhat neglected in the past because the conditions were not favorable to its adoption. The necessity of a wattless magnetizing exciting current which must be supplied from the system, is a great disadvantage in a number of cases. But with large city power stations operating synchronous apparatus, or an extensive high voltage overhead transmission system, with large capacity charging current, the conditions are much more favorable to this type of generator. In any system such as that of the Southern Power Company the arrangement suggested would be: synchronous units installed in one or two of the large power stations and induction generators in all the smaller stations. The generator units in the smaller stations would run continuously on the circuit without attention, the governor of the prime movers regulating the load, while the voltage on the system would be controlled from the large synchronous power stations. The suitability of the induction generator for any such system would depend to a great extent on the speed at which the units operated. the voltage for which they are wound, and the power-factor of the load on the alternating-current distribution system. And, in any case, the advisability of adopting or not adopting such an arrangement of induction generators in any large complicated system such as that of the Southern Power Company could only be decided after the system has been laid out in detail, and all the economic and engineering features been given due consideration. My object in bringing forward the induction generator at this time is not that it is considered advisable to adopt this type of generator universally in such installations, but that as conditions are gradually changing and becoming more favorable to the adoption of this type of unit, it now deserves more attention than it has received in the past.

Chas. F. Scott: Mr. Lee's paper besides presenting the general conditions confronting the Southern Power Company, shows also a new stage in the development or evolution of electrical transmission.

The high tension transmission system of several years ago consisted of a generator, raising transformer, line, and a lower transformer with some distributing lines. The transmission system consisted of a single transmission line from one generator to one substation. More complicated designs rapidly developed. In one type a number of power plants supplied a single point; possibly Los Angeles may serve as an example which receives incoming power from several directions. Then, again there is another type in which power is generated at one point and is distributed by various transmission lines in different directions, each of these lines supplying stations at various points en route; Niagara Falls is typical of this condition.

In the case of the Southern Power Company we are apt to think that operating at 100,000 volts is its great feature, but a statement of Mr Lee's shows that there is something more notable. He says now that this is not a high-tension transmission system, but a high-tension distribution system. There are many scattered power houses, and many distribution centers.

A number of years ago, when the Niagara plant was being laid out and great interest was concentrated on the generators of mammoth and unique form, one of my colleagues, who was engaged in the development of switching apparatus, made a remark which struck me on account of its originality and novelty. He said that the great difficulty and the big problem in large electrical work would not be in the generators, but in the switching and controlling apparatus.

I have thought of that remark many times since, and I believe it is more true to-day than when it was first spoken. In a plant with high-pressure circuits and many receiving and distributing points, such as has been described this morning, the problem of switching and controlling apparatus constitutes the large electrical problem. So that this plant illustrates, not only the new commercial-political relations, as Mr. Lee has pointed out but also marks a new stage in electrical operation and the types of apparatus which are required.

In brief, the operating conditions, the inter-relation between stations and operators, involving such questions as those Mr. Thomas asked, and such questions as Mr. Waters brought out a moment ago in their discussions—these are the large and important elements upon which the success of the plant will depend.

The relation of electricity to the conservation of energy is one which has received attention at the hands of our President in one of his papers before the Institute, and it seems to me Mr. Lee has brought out some features which are descriptive, in a large and broad way, of the larger service which electricity will have in the conservation of our natural resources. It not only saves the waste of water power and enables it to be utilized, but by entering into a whole region, by making a power system of a whole state, it equalizes the different variables which occur in the operation of each individual system which Mr. Lee has pointed out. Now, by interconnecting many plants into one general electric system covering the whole stage, these individual elements or variations can largely be wiped out, and we can get that general average which means the highest general efficiency, so that we equalize power, and we save power, and furnish a better and cheaper power, as was brought out in the discussion yesterday.

With regard to the relations of the engineer to the general problem, I would almost disagree with Mr. Lee, when he apparently limits the function of the engineer to the purely technical problems. He says in the beginning of his paper that some of the problems are commercial rather than engineering. Taking our natural resources, and applying them most efficiently under the conditions which exist, I think, like most of the things which he has brought up, can properly be placed under broad engineering. I think he is right also in stating that the proper way for engineers to handle the large conservation problem is by attacking the problem in a large way and getting efficient results. And I believe that the general common sense of the American people is such that they do not object to having things done in a large way on a sound engineering basis, but what they do object to is having them done on a false and unjust social and commercial basis. Our commercial and political friends should recognize the same kind of standard that the engineers work to, high efficiency, the greatest good to the greatest number, on a fair and just basis; in fact engineers are setting the standard of principles which should be adopted in commercial and political life, as they must practice them in their professional life.

In talking with one of the older men in this community, who has seen things build up in the South for many years, and in speaking of the new life which has come to the district, and the new methods in cotton mills, he said that pioneer work of this kind requires imagination, initiative, and nerve. He said that is what the Southern Power Company has, and I am sure we all agree with him.

Edw. W. Shedd: Mr. President and gentlemen, I have been exceedingly interested in the paper that has been presented by Mr. Lee, and I desire to offer just one suggestion which I think has not been touched upon in the discussion, but which Mr. Lee brought out in his paper, and that is the great importance of the question of transportation; and I am sure that you will all agree with me that that is a question of transcendant importance, and it is a question which must be met and worked out if the fullest development of our southern water powers is brought to pass, and it is a question which I think works in most uniformly and nicely with the question of hydroelectric development.

For nearly two years I have been working in this territory, purposely selecting the territory in which the Southern Power Company is operating, upon a system of railways which is designed to meet the needs of the territory as regards transportation, and which I think in the near future is bound to be built.

I want also to emphatically endorse the suggestion of Mr. Lee and others who have discussed the paper as to the value and importance of engineers and every one else educating the public, especially perhaps the political public, as to the advisability of giving to these quasi- public corporations sufficient rights, particularly in the way of eminent domain, to enable them to carry out all their important developments which are in progress. It seems too bad that many valuable developments are held back by the narrow mindedness of some one man who thinks he has a big corporation to deal with; he will get fifteen times the value of his land, just because the corporation wants a right-of-way through it. Such procedure holds back development in many cases. It is the duty of every electrical engineer and civil engineer, lawyer and banker, to try to educate the public and to work with the legislators, so that a broad-gauge policy can be followed in these matters.

Speaking directly to the point, it has been suggested that we should develop something that would use the water power when the hydroelectric companies have a surplus of water, and when it is not being used for other kinds of business. It has occurred to me to-day, and it has occurred to me many times before, that one very large use, possibly of this power in the night time could be developed by operating a system of railways, particularly in the section of the country in which the Southern Power Company and other hydroelectric plants are operated, hauling the freight in the night. A large amount of power can be used at night in hauling freight, for I see no reason why the freight business could not be done in the night time when there is a surplus of hydroelectric power available. It is my purpose to use hydroelectric power for the operation of railways in the district of the Southern Power Company, carrying freight at night.

Perhaps this is not the place to bring it forward, but the idea has occurred to me that it might be desirable, if it were constitutional to subsidize such industries as water power developments, railways, etc., in the way, possibly of exempting their bonds from taxation. It might be possible in this way to induce the banks and trust companies in the south, which are pretty well supplied now with money, and find difficulty in lending it, to take some of the bonds, of these enterprises as this would make them more attractive as an investment.

It has occurred to me that this might be done by the partial or complete exemption of taxation on bonds issued by hydroelectric plants, and on railways, exclusively within the state of North Carolina, and held, perhaps, exclusively by investors residing in the State of North Carolina. It looks to me as though something of this kind could be worked out very satisfactorily, and this would make the railways and the hydroelectric plants, as you might say, a board of trade, which would be working for the development of the entire country, and at the same time furnish a more attractive investment for the money on deposit in North Carolina, to be used only in this State, and in other states, if such states do the same thing.

President Stillwell: Mr. Scott has already referred to the first of the points which I noted in listening to Mr. Lee's paper, namely, his apparent contrasting of the ideas of engineering considerations and commercial considerations. Engineering, as I understand it, when applied to the solution of these large industrial problems, means the application of commercial business judgment, reducible to terms of dollars and cents, to those problems; that application being based, however, upon special study of the technical underlying problems which are essential as a foundation for the general solution. I think if we were to use the words "technical" and "commercial," in making a contrast, rather than "engineering" and "commerical," we should place the matter in about the right light, because we do not want the community to get into the habit, which I am sorry to say it has acquired in part, of looking upon engineers as men who are incapable of drawing practical deductions. The engineering which is of the broadest kind, is precisely the kind which Mr. Lee himself, a member of the Institute, is carrying on. He has applied broad business judgment, based on technical knowledge, to the solution of industrial and commercial problems. Immediately, that raises a question of engineering responsibility, and that is a point I want to say a word about.

We have now throughout the country an abnormal number of hydroelectric enterprises in the hands of receivers. In every case that I have had occasion to investigate or have learned about, and I have come in touch with a number of them, the failure has been due to the fact that at the outset the proper kind of commercial-engineering brains were not brought to bear on the problem. I do not know an important case where the thing that caused the enterprise to fail could not or should not have been foreseen. Engineers are too apt to allow themselves to be hurried and pressed by the promoter. In one important case where an estimate had to be revised to an extent which involved the raising of about $2,000,000 in addition to the original amount provided for by the financiers, I am told that the engineer made the excuse that he was allowed only one week to investigate that problem. That excuse is an indictment of the engineer himself. Any man who could undertake to pass on a matter involving large amounts of other people's money, or small amounts, on a matter of such magnitude, in such a short time, ought to resign from the engineering society and get out of the business. He does not belong there.

Mr. Lee made reference to the subject of condemnation of rights for transmission lines, and also of the lines which are essential to the hydroelectric development. Now, there is a point where I believe we can use our influence, not collectively, perhaps, but individually with our congressmen and friends in the legislatures, in a perfectly proper manner, and in a manner that will redound to the benefit of our engineering organization and of engineers as individuals and of the community at large. We have in the country two classes of public utility corporations, aside from those which have to do with the cities, the gas companies and the railways, and now we have to do with these great transmission and distribution systems utilizing water powers. The railways have the right of eminent domain. In general, the power companies have not. Is there any possible reason and logical common sense why they should not have this right? The gross earnings of the railways of the United States are approximately $3,000,000,000, a year. The gross value of our manufactured products is approximately $20,000,000,000 a year. This utilization of power means a general tendency to decrease the cost of the manufactured product. It also means in many cases, and in more cases to come, a reduction in the cost of transportation. Economically considered, therefore, every reason that exists for conferring upon the railways the right to condemn, exists with increased force in the case of the power companies distributing energy for the very many purposes to which the community applies it. Now, this question of natural monopoly must be met, and we must meet it with an effective answer. As citizens many of us are lined up on that side of the question, but we have to face the fact that, at any rate, there is going to be in this country government regulation of rates, especially the rates of public utility corporations. The right of the state has already been upheld in the case of the Consolidated Gas Company in New York, where the decision of the supreme court of the state of New York was appealed to the United States supreme court, and in that case it was definitely decided by the higher tribunal that the state has the right to regulate rates. Now it seems to me that the answer to give to those people who are objecting to a natural monopoly in water power is this—that it is absolutely unnecessary to retard the development of these enterprises at this date, for the reason that just as rapidly as they place themselves in the position where they are imposing upon the community by charging excessive or unfair rates, the state is in the position to intervene and regulate these rates. This practice of conjuring up something that might happen in the dim and distant future in the way of fixing rates is too remote an excuse for justifying any possible retardation in the forward movement of this extremely important conservation, because conservation is, in this case, most emphatically utilization; but we must have our answer, and the answer is not that our rates are moderate—they won't believe it. We can give that answer to those who will believe it, but most of the people will discount such a statement; but our answer should be this—that just as soon as this is a real danger, and not an imaginary one, the state can intervene, as established by the decisions of the supreme court, and fix just and equitable rates.

I think it is the duty and a part of the business of engineers to take a hand in public affairs. I do not see why 20,000 engineers in this country should sit back and let other people, five per cent of whom do not understand the facts necessary to the commercial solution of these problems, pass upon them, while the engineers sit on the fence and watch them do it. The engineers should get into the game early and meet the people who are interested in these things in a social way, and otherwise, and endeavor in every possible way to educate them. That is what they need. We have talked with many of them, including Mr. Ballinger and Mr. Pinchot, and have seen none of them who do not admit that they need ideas in regard to the practical, technical and economic bearing of some of these questions, which some of us are able to give them.

W. S. Lee: Referring to Mr. Thomas' remarks, he asks about the speed of wheels. We have on the system different heads, different size ponds, and consequently the plant with the small ponds must be run a longer number of hours, and in the case of the larger ponds a shorter number of hours, but with a larger peak load. All the waterwheels permit a certain variation of head and maintain the same frequency. We endeavor to reduce these heads as little as possible, it being our practice in extremely low water to put in our steam auxiliaries in the early part rather than in the latter part of the week. While originally we had the idea that we would run the water as long as we could, and at the end of the week put in the steam to help out the week's load, we find by keeping the head up in the earlier part of the week we get more power out of the system.

Mr. Thomas also asked about voltage regulation. In order to meet the conditions with which we were confronted, that is, differences in voltage, we got out a standard set of specifications giving a list of taps which we were to have on all of our high tension transformers. This calls for a higher voltage to be run on the plant during the time of our heavy load hours. When the load goes off the cotton mills at six o'clock in the afternoon, the voltage on the whole system is lowered. This takes care of the drop in voltage in the line, the transformers being tapped with reference to the distance from the power house. The line which it is hardest to control the voltage on is the line that is not loaded.

Mr. Thomas also asked some questions about sectionalizing the system. I will say that that is a question which I have been dodging in a way. We have certain lines that go to stations or distributing points. We term them switching stations. From these switching stations the lines may branch out into a greater number of lines to cover different territory. We then go on to another point and break the line up into several more lines, supplying different points. All of these stations are provided with automatic switches or fuses. We can sectionalize the different parts of the system from time to time, putting one plant either on one side or the other.

Mr. Thomas also is rather disposed to criticise the voltage we are going to, but I do not think I will answer that because he answered that point himself. He stated that perhaps it would be a good thing to use these higher voltages to run around and come back over greater distances, where there might be a reason for doing this. That is what Mr. Burkholder does. It is fifty miles from here to Great Falls, and Mr. Burkholder does not hesitate to take the current to Salisbury and back again, and by the time it reaches Charlotte it has traveled 150 miles.

Mr. Thomas also asked some questions regarding the distribution of load. That is a question we do not know how to answer. You may have an idea that one particular section of this system is going to develop and you will be surprised to find some other develops much faster.

Regarding the remarks he made as to the location of plants on the outskirts of the district, that is not possible, because the bulk of the power is brought up country and there may not be any water power in that particular district.

Mr. Rushmore referred to steam auxiliaries and synchronous condensers. In connection with that, I will say that we are now installing some of this apparatus at Greenville, South Carolina; we are installing a 10,000-kw. steam-turbine, which will operate as a synchronous condenser, and we are arranging to install another similar set at a point we have not yet decided upon, which will have a capacity of 6,000 kw.

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A PRACTICAL METHOD OF PROTECTING INSULATORS FROM LIGHTNING AND POWER ARC EFFECTS

BY L. C. NICHOLSON

The problem of adequately protecting a high-tension transmission line against injury by lightning is an important one. Various solutions have been proposed, but it is generally conceded that complete protection of high-tension porcelain insulators from destruction by lightning effects has not been attained. Grounded overhead conductors, relief gaps on insulators, lightning rods supported on the transmission line structures or on separate structures alongside, and station-type lightning arresters at points particularly exposed, are some of the principal preventive devices employed, any of which serves to ameliorate conditions, but none of which affords ideal protection to the line.

The 60,000-volt transmission lines of the Niagara, Lockport and Ontario Power Company from Niagara Falls to Syracuse and other cities in western New York, were placed in operation in July, 1906, just in the midst of the lightning season, and without any of the usual methods of line lightning protection. Troubles developed which, though not unexpected, proved of serious consequence to the successful transmission of power during lightning storms. There was little opportunity in that season to adopt any corrective measures, either experimentally or otherwise, but in the following years the company has exerted every effort to ameliorate these troubles.

The experience of four years has served to indicate something of the real nature of lightning effects which result in insulator failures, and has led to the development of an inexpensive and efficient means of protection. The object of this paper is to relate the experiences and experiments leading to the protective measures finally adopted, which from one summer's trial appear to be sufficient.

This plant was thoroughly described by Mr. Ralph D. Mershon in a paper presented at the Niagara Falls Convention* June, 1907. For purposes of reference, Fig. 1 shows the extent and description of lines, the connection and approximate capacity of the stations.

Figs. 2, 3, and 4 show types of line structures employed. In all cases insulator pins are of steel and are grounded.

Fig. 5 shows the principal insulator used, and, with the exception of a few smaller ones of the same general design, the only type of insulator employed until 1909. This is known as the "3-part main line" insulator. Its principal dimensions are:

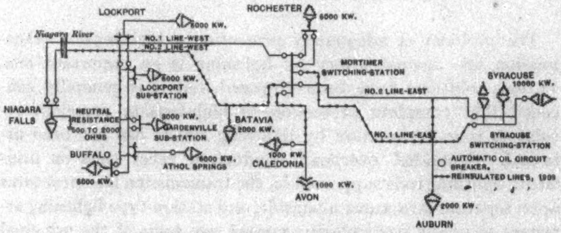
LOCKPORT
6000 KW.
ROCHESTER
6000 KW.
Niagara River
NO. 1 LINE-WEST
NO. 2 LINE-WEST
MORTIMER
SWITCHING-STATION
6000 KW.
LOCKPORT
SUB-STATION
SYRACUSE
10000 KW.
NO. 2 LINE-EAST
NIAGARA
FALLS
NEUTRAL
RESISTANCE
500 TO 2000
OHMS
3000 KW.
GARDENVILLE
SUB-STATION
BATAVIA
2000 KW.
NO. 1 LINE-EAST
SYRACUSE
SWITCHING-STATION
BUFFALO
6000 KW.
6000 KW.
ATHOL SPRINGS
1000 KW.
CALEDONIA
AUTOMATIC OIL CIRCUIT
BREAKER.
REINSULATED LINES, 1909
1000 KW.
AVON
2000 KW.
AUBURN

FIG. 1.—Diagram of transmission lines and stations—1909

Diameter of headpiece, 14½ in.; diameter of intermediate shell, 13 in.; diameter of center shell, 11 in.; length of intermediate shell, 12 in.; length of center shell, 17 in.; height over all, 19½ in. The dry flash-over voltage, that is, the voltage which will cause a flash-over when the surface is dry and clean, is 195,000. The wet flash-over voltage at 1/5 in. per minute precipitation at 45 degrees is 120,000.

Electrical tests on these insulators before their erection on the line consisted of 75,000 volts, three minutes on each part before assembling. The complete insulator was not tested after assembling.

During 1906 only one line was in service to various points. By the beginning of the lightning season of 1907 the second (duplicate) line was placed in service, making a total mileage of 400, containing 7000 structures and 23,000 insulators. Except for the addition of a few single branch lines from time to time, the lines have been virtually the same for three years.

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* TRANSACTIONS A. I. E. E., Vol. xxvi part ii, p. 1273.

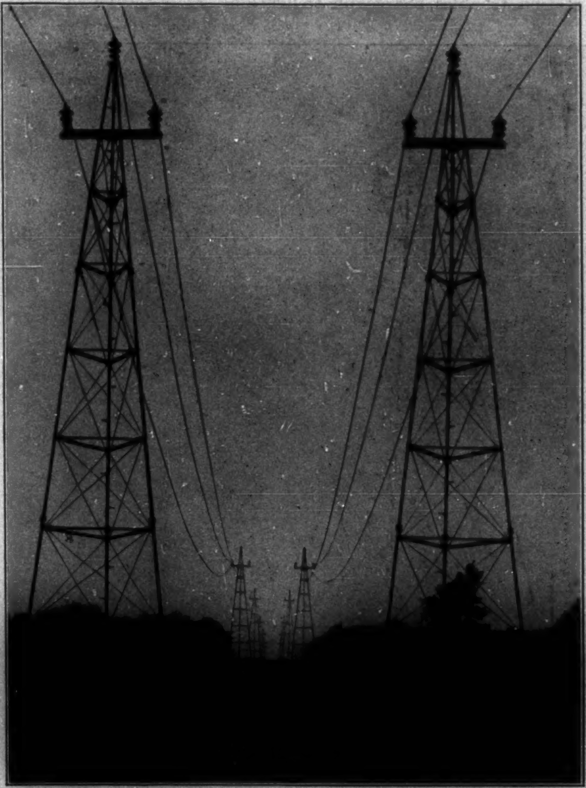


FIG. 2.—55-ft. tripod pipe towers

Switching facilities and general operating conditions, however, have been constantly improved. Since early in 1908 automatic oil circuit-breakers have been used in the duplicate lines at all important stations and paralleling points, making possible automatic sectionalizing of lines and a quick restoration of power in case of an interruption.

Lightning troubles have been entirely confined to the line. No station troubles, chargeable to lightning, have developed.

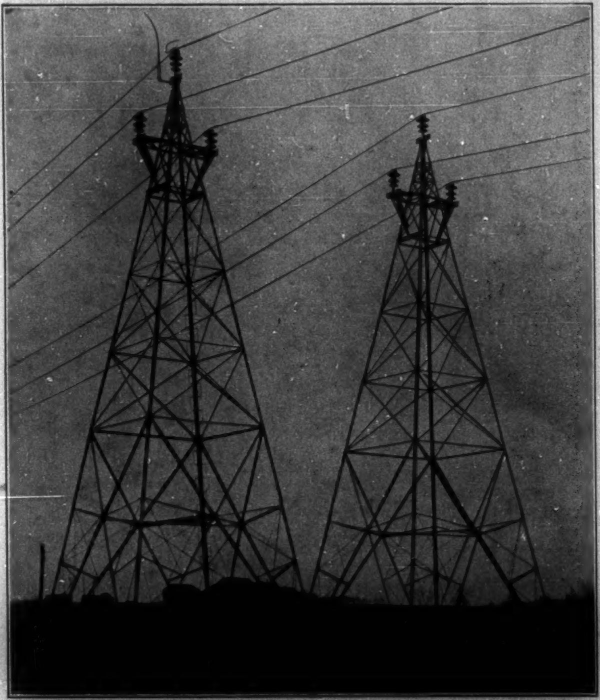


FIG. 3.—55-ft. structural steel towers, showing a relief gap, as used in 1907

Experience clearly shows that lightning in the vicinity of the line induces high potentials between the line conductors and earth. This potential causes one or more insulators in that immediate vicinity to flash over or puncture, or to be shattered in some part or parts, even though no flash-over or puncture occurs, or to be shattered by the power arc following the initial flash-over or puncture. These various causes intermingle their effects so as to obscure the first cause. Thus it has been found that insulators may be shattered completely either by pure lightning stresses, or by the heat of a power arc which follows the initial discharge from conductor to pin over the outside surface. Moreover, an insulator may puncture by lightning, and subsequently be shattered by the heat of the power current passing through the puncture, in which case it is impossible to say whether the puncture preceded the shattering or vice versa. A fairly concise idea of the nature and mag-

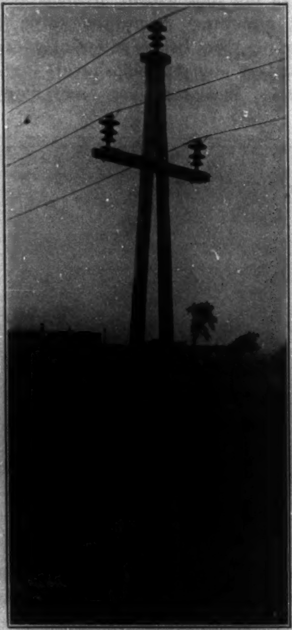


Fig. 4.—35-ft. wooden A-frame structure

nitude of the destructive forces may be gained by a study of the broken insulators in place.

Fig. 6 shows a collection of twenty derelicts, resulting from a single severe storm, and gives a fair representation of how insulators are destroyed by lightning in combination with high-power effects.

The usual caes of line disablement involves a single insulator, which is either punctured from the cable or tie-wire to the top of the pin, or, being sufficiently strong to resist puncture, is broken by the flashover arc. Frequently several neighboring insulators are more or less damaged by what appears to be the effect of sudden mechanical forces which shatter or break the shells very much as a hammer blow would destroy them.

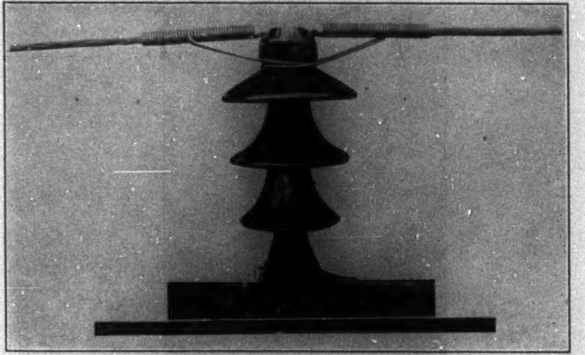


FIG. 5.—3-part main line insulator

Extreme cases infrequently occur when many insulators in a restricted locality are entirely destroyed. Such disturbances usually center at a particular line structure on which all the insulators may be entirely destroyed, and one or more insulators on several adjacent structures in each direction destroyed or injured, the injury decreasing in severity away from the focus. Even in the most severe cases, however, the entire effect is confined to within 2,000 feet of the line. Such accidents are atuttribed to direct strokes on or very near the line. The mechanical forces exerted on insulator parts in such cases appear to be enormous, breaking the porcelain into small bits of irregular and curious shapes, and distributing them over the right-of-way for several hundred feet. Fortunately these extreme cases are of rare occurrence and do not enter largely into the lightning protection problem.

Just where direct stroke effects leave off, and just where induced potential effects begin and end, is, of course, indefinite. It is definitely known that a stroke 500 feet distant may cause a flash-over or puncture. It is thought that disturbances may be felt from bolts 2,000 or 3,000 feet away, this being also determined by the size of the discharge, and perhaps by electrostatic conditions in general.

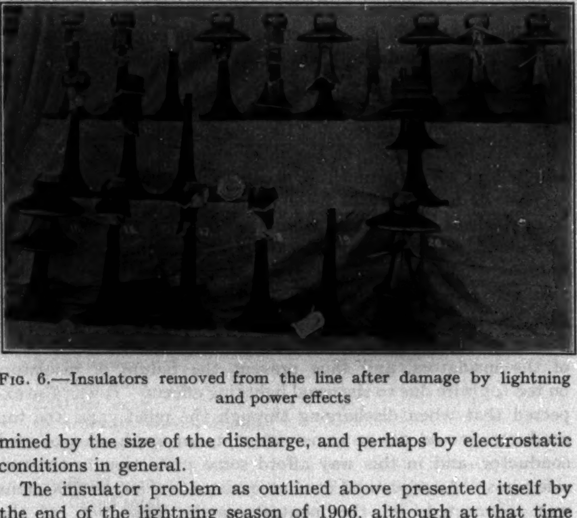


FIG. 6.—Insulators removed from the line after damage by lightning and power effects

The insulator problem as outlined above presented itself by the end of the lightning season of 1906, although at that time its nature was not appreciated as fully as it became later in the light of the subsequent experience. Thirty-five insulators were disabled by puncturing or shattering, out of a total of 12,000 installed. These breakages occurred on eight different occasions and consequently caused as many extended interruptions to parts of the service. In addition, there were ten momentary interruptions caused by short-circuits or grounds which tripped the controlling circuit-breaker, but did not disable the line.

Analysis of the insulator failures with respect to their location showed a very remarkable result. The number of insulators disabled on the top wire was four times the number disabled on a single side wire, or twice the number disabled on both side wires.

This result formed a basis for corrective measures which were taken previous to the lightning season of 1907. These devices consisted of relief gaps installed on insulators at regular intervals on the top wire of both duplicate lines, and the installation of high resistances in the neutral earth connections of star-connected transformers. Fig. 3 shows the type and construction of the relief gap which was employed.

These gaps were spaced 2200 feet on approximately 240 miles of line and 4400 feet on 100 miles, while on 60 miles no gaps were installed. At the time of selecting these spacings there was very little data for guidance. The only definite information available was that during 1906, before the lines were used, insulators were destroyed within a mile of a point where all three conductors were short-circuited and thoroughly grounded. The 2200- and 4400-foot spacing of the relief gaps on the top wire was adopted in an experimental attitude, the intention being to increase or decrease these distances as future experience dictated. The width of gap first adopted was six inches, corresponding to a discharge voltage of 70,000 volts, depending more or less upon weather conditions. This was also a subject of experiment.

It was intended by proper spacing and setting of the relief gaps, to limit the maximum possible voltage between top conductor and earth to less than the puncture or flash-over value of the insulators, and thus prevent the failure of insulators on the top wire due to the usual lightning effects. It was also expected that when discharging through the relief gaps, the top conductor would act to some extent as an overhead grounded conductor, and in this way afford some protection to the two side wires. An adjustable concrete resistance of 500 to 2000 ohms was connected in the neutral earth connection of the sending transformers, and 5000- to 10,000-ohm resistances at five different sub-stations in the neutral earth connection of star-delta connected receiving transformers. The purpose of installing these resistances was primarily to limit the discharge current to earth from the top wire through the relief gaps to a value which would not disturb operation, and the arc of which would quickly follow up the horns of the gap and discontinue. In the same way it was thought that these resistances would limit the power-current over an insulator containing no gap, in the event of a flash-over, to a value which would not work such havoc to the insulators as had formerly occurred when operating the system with thoroughly grounded neutrals. The 5000- to 10,000-ohm sub-station resistances were, of course, not necessary to attain the end sought. They were installed as a precautionary measure against abnormal potentials which might accompany grounds on the system. Their use was later discontinued, all neutrals except that at the generating station being insulated.

The operating results of the lightning season of 1907 did not fully justify the use of the relief gaps from a theoretical standpoint, and showed them to be rather an objection than an advantage from a practical operating standpoint.

It was early apparent that the gaps perfectly protected the insulators containing them, but that their protective influence was felt very slightly a short distance away on the same conductor, and was not felt at all on the two lower conductors. This was true with gaps set as low as 4½ in.

The following tabulation shows the season's results:

	Insulators disabled on top wire	Insulators disabled on both side wires
At a relief gap	0	6
220 feet from the nearest gap	2	3
550 feet away	15	17
1100 feet away	11	13
2200 feet away	4	1
On a 60-mile section containing no relief gaps	9	5
	—	—
Total	41	45
Grand total		86

Insulators on line—23,000.

Relief gaps on line—750, approximately 25 per cent of which discharged one or more times.

These results demonstrate the extreme localization of lightning effects and the difficulty with which the charges travel along a conductor.

It appears from this table that the net effect of the use of the gaps was to save some insulators on the top wire. The number of line breakdowns was not reduced, while voltage disturbances and momentary interruptions were numerous. For this reason the relief gaps were removed before the lightning season of 1908. The grounded horn was left in place to act as a lightning rod. The concrete neutral resistance at the generating station was retained to prevent short-circuits between any one phase and ground.

A study of the insulator failures of 1907 showed that the majority of them were due to puncture, usually from the tie-wire in the neck to the top of the pin. A few punctured vertically from the cable to the pin. Approximately 25 per cent, and perhaps more, were shattered by power arc following a complete or partial flash-over. Comparatively few, it is believed, were shattered by direct stroke, although about 40 were injured by lightning stresses, but were not incapacitated thereby.

In view of the large proportion of punctures, it was decided to apply high potential to the lines and to weed out the weak insulators. This proved to be a slow and expensive process, so that very little was accomplished before the advent of lightning in 1908. A three-minute test of 100,000 volts to ground was applied to 109 miles of line containing 4000 insulators, and resulted in the puncture of 80.

These tests showed what there was already good reason to suspect, *viz.*: that the insulators were not tested sufficiently before erection, and that many of those on the line could not resist lightning stresses, and some were liable to fail from abnormal voltages incident to operation. As stated above, the insulator parts were tested to 75,000 volts each, but no test was made on the assembled insulator.

The lightning season of 1908 was a particularly severe one, resulting in the destruction of 226 insulators and the injury of 100 more.

The failures may be classified approximately as follows:

1. Punctured:

Top wire	75
Side wires	39
Total	114

2. Shattered by direct stroke:

Top wire	22
Side wires	9
Total	31

3. Shattered by power arc, following flash-over:

Top wire	56
Side wires	25
Total	81

The 100 insulators which were injured were damaged by lightning stresses, or by power arc effects. They were still operative, however, and were replaced at convenience.

The lesson of the year was not new, but it showed more forcefully than had been realized before, that even if all insulators were capable of resisting puncture, they would continue to be shattered by a power arc following a flash-over. It was argued that by the proper testing of all insulators puncture could probably be prevented, but the fact that such a large number had been already destroyed by flash-over gave little reason to suppose that insulator losses and line interruptions could be materially reduced by providing puncture-proof insulators. They must be also fire-proof.

The only practical way of making the insulators puncture-proof was to remove them from the line, test each one to its dry flash-over voltage and return the perfect ones to the line. There was some question as to whether or not such a test would be effective, since an insulator which would flash over under 25-cycle voltage from a testing transformer, might puncture under the sudden attack of a lightning shock. However, the fact remained that insulators, presumably sound and dry, had flashed over in service because of lightning, rather than puncture, and this justified the belief that a 25-cycle dry flash-over test was sufficient. Subsequent experience has verified this conclusion.

A device for rendering insulators fire-proof, or rather proof against injury by power arc in the event of a flash-over, was developed to meet an obvious need. As shown by Fig. 7, this device consists of two metal rings concentric with the insulator, a lower one which is situated near the base being considerably larger in diameter than the insulator parts, and supported by grounded metal risers attached to the pin; and an upper one somewhat larger than the neck of the insulator, just opposite the tie-wire, suspended from the transmission cable, and electrically connected to it. Details of construction are evident from the figures.

These rings serve as electrodes, to which the power arc automatically transfers immediately after its formation between the tie-wire and pin, over the surface of the insulator. When holding between these rings, the arc is removed sufficiently from the insulator to prevent injury to the porcelain by heat.

It was determined experimentally that the intense and concentrated heat at and near the ends of a large power arc is largely responsible for the damage wrought. This is particularly true of the lower terminal which passes up the pin to the heart of the insulator and shatters it. In other words, the insulator is broken from the bottom upward, by the lower end of the arc. The upper terminal, located on the tie-wire, is not so destructive, on account of the tendency of the arc to flare upward and away from the porcelain. If, however, the very crater of the arc comes into actual contact with the porcelain, by reason of being located on the nether side of the tie-wire, or by reason of burning the tie-wire in two, which it may do if it remains at a single point, the headpiece of the insulator will be broken.

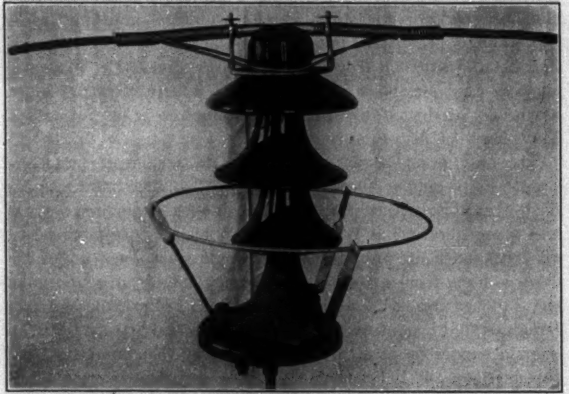


FIG. 7.—Arcing rings, to prevent injury to insulators by power effects

Considerable experimenting with high power arcs showed that the lower portion of the arc was averse to assuming anything like a horizontal position. It very much preferred not to make the bend about the base of the insulator to reach the pin. Thus, it was found that the lower arcing ring would take the arc immediately after its formation to the pin, (which was accomplished by means of a fuse from tie-wire to pin, placed well up under the insulator parts) almost irrespective of the location of the ring with reference to the base of the insulator. On a quiet summer day, with practically no air movement to drive the arc away from the insulator, and naturally cause it to attack the ring, it was found that the arc instantaneously transferred from the pin to the lower ring, even though the ring was 20 in. larger in diameter than the base of the insulator, and as much as 4 in. below the base. The flaring nature and large size of these arcs, together with their tendency to assume an upright position afford the explanation of these results.

In the absence of wind it was apparent that the arc traveled rapidly from place to place around the insulator, and did not remain in any one place long enough to burn the tie-wire seriously. For this reason the headpiece of the insulator did not suffer, except perhaps to lose a little glaze. Under wind conditions, however, the arc hides behind the insulator on the leeward side and remains at or near one place on the tie-wire, sometimes burning it in two, and by coming into actual contact with the porcelain causes a breakage of the headpiece, but only the headpiece. The cure for this condition proved to be the use of a second ring about the head of the insulator, separated at all points from the porcelain. It was located just opposite the tie-wire, and of sufficient thickness fairly to resist serious burning.

Numerous tests were made, using as high as 30,000-kw. generator capacity, which under the short-circuit conditions of the test delivered 1200 amperes at an initial voltage of 60,000. In no instance was an insulator when equipped with both arcing rings damaged to the slightest extent. Fig. 8 is a night photograph of a 30,000-kw. arc. An insulator with arcing rings, in the midst of the fire, does not show. It was perfectly whole and fairly cool after this experience.

A typical case showing the manner in which insulators are destroyed by power arcs is shown in Fig. 13, which depicts an insulator destroyed in service by a power arc following a flashover by lightning.

The possible damage to the transmission cable by burning in the event of the upper terminal of the arc traveling out along the cable, owing to wind blowing in the direction of the line was fully dealt with experimentally, with and without arcing rings. It was found that a breeze of 3 miles per hour (estimated) parallel to the line was sufficient to drive the arc out on the cable to a distance of 12 feet in four seconds. This was true whether the insulator was equipped with arcing rings or not. The amount of burning by three successive four-second applications of a 1200-ampere arc is shown by Fig. 9. It will be noted that the cable is not damaged materially at any one place, but that the scarring is distributed. This cable, which is 214,000 cir. mils aluminum, still retains 95 per cent of its original strength.

FIG. 8.—Night photograph of a 30,000-kw. 1200-ampere arc on an insulator equipped with arcing rings

As to what direction of wind, with reference to the line, will just cause the arc to go out on the cable, it is concluded from test results and observations on lines in service that with sloping ties such as are used on these lines it is necessary that the wind blow at an angle less than 30 degrees to the direction of the line. This value is not materially influenced by the presence of arcing rings.

Generally speaking, it is true that the transmission cables are not more exposed to burning with arcing rings than without them, and in neither case is the burning at all serious. Fig. 10 shows a section of cable blistered in service by a short-circuit arc from a generating capacity of approximately 60,000 kw.

The arcing tests outlined above showed considerable latitude in the effective location of the lower ring. In addition, potential tests were made to determine the effect of this ring in various positions upon the flash-over voltage of insulators. It is evidently possible to set the ring high up on and close to the insulator, and thereby materially to decrease the effective insulation, since the initial discharge may pass to the ring, either from some point on the insulator or vertically downward from the cable, instead of passing over the entire insulator to the pin. The extent of this influence not only depends upon the location of the ring, but in a fortunate way upon the condition of the insulator surface. Thus the dry flash-over value may be reduced as desired, to protect against voltages which are apt to puncture the insulator, while the normal minimum wet flash-over voltage need not be reduced. The insulator is thus left to develop its full flash-over value when most needed, and when least likely to result in puncture.

Fig. 9.—214,000 cir. mils aluminum cable burned by three applications of a 1200-ampere arc

These effects appear graphically in Fig. 11. Curve *a* represents the ordinary performance of an insulator on a metal pin under spray, the flash-over voltage decreasing with the increase of water. Curve *b* shows its performance with the arcing ring so proportioned and so placed with reference to the insulator parts as to effect a considerable reduction in the normal dry flash-over voltage, the initial discharge being to the ring instead of to the pin, without reducing the normal minimum wet flash-over voltage. Point *x* designates neutral conditions at which the initial discharge is as likely to strike to the ring as to the pin; at slower precipitation it strikes to the ring, and at higher rates to the pin. Of course, different insulators and different rings give different curves, but in any case it is possible to determine by experiment the size and setting of a ring necessary to accomplish definite results, within certain limits. Comparatively long insulators lend themselves best to such protection, and other things being equal, they need it most.

An important advantage arising from the use of a ring for this purpose, especially on long insulators of the type under consideration, is that the total reduction of voltage is effective on the lower part of the insulator, and relief is given where most needed. Thus it is well known that in an insulator of the pin type, the shell next the pin is subjected to more than its proportion of the total voltage acting. The potential gradient from the top of the grounded metal pin to the tie-wire in the insulator neck is believed to be such as to impose about 50 per cent of the total applied potential upon the pin-piece or inner shell of the insulator under consideration. At dry flash-over, therefore, the inner shell must resist a puncturing e.m.f. of something near 100,000 volts. This excessive potential on the inner shell may be reduced as much as desired by placing the lower arcing ring in proper proximity to the edge of the second or intermediate shell. A definite spark-gap is thus provided in parallel with the

FIG. 10.—214,000 cir. mils aluminum cable burned in service by a short-circuit arc from six 10,000-kw. generators

lower part of the insulator, insuring the inner shell against puncture and, therefore, in all probability, the entire insulator.

Moreover, when a discharge of short duration occurs from, say the edge of the second shell to the lower ring, it is evident that the resistance of the surface of the insulator above the edge of the second shell is in series with such a discharge and has some deterrent effect upon the passage of the power-current. This is purely an operating advantage. Several cases have been discovered on the lines in service where such action has occurred. It is believed to be infrequent, however, since if an insulator flashes over by lightning, either partially or totally, the power-current is very apt to follow.

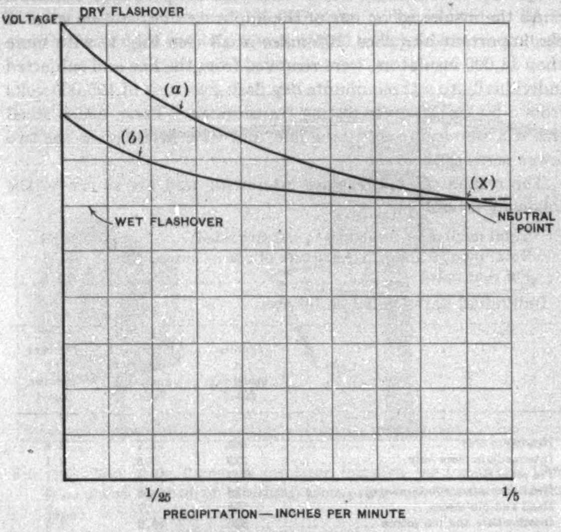


Fig. 11.—Flash-over characteristics of an insulator under spray, with and without arcing rings

(a) Without arcing rings

(b) With arcing rings adjusted to lower the "dry flash-over" without affecting minimum "wet flash-over"

In addition to these considerations, the earth potential brought up around the insulator undoubtedly has an effect in ameliorating the puncturing tendencies of high potentials, and provides more favorable electrostatic conditions at times of sudden shock. On this account it was thought that the long three-part insulator would suffer very much less than formerly from breakage of parts by lightning strains, and this has been fully substantiated by experience.

Before the summer or lightning season in 1909 a corrective programme as outlined below had been adopted and executed.

All the insulators on one of the duplicate lines and on some of the important branches, 195 miles in all (see Fig. 1) with more than 11,000 insulators, were removed from the line and subjected individually to a three-minute dry flash-over test of 195,000 volts from a 50-kw. 25-cycle testing transformer. Those which stood this test were returned to the line, and were installed on the two lower wires exclusively.

The results of this test are interesting and are shown in the following tabulation:

Total number of insulators tested (recorded)	10480
Total number failed by puncture of one or more parts	4172
Per cent failed	39.5

Individual parts failed as follows:

	Number of insulators failed	Per cent of number failed	Per cent of number tested
Headpiece only	504	12.1	4.8
Intermediate piece only	229	5.5	2.1
Pin piece only	2317	55.5	22.1
Head and intermediate pieces	34	.8	.3
Head and pin pieces	28	.7	.2
Intermediate and pin pieces	830	19.9	7.9
All three parts	230	5.5	2.1

It is seen that 81.6 per cent of all failures involved the pin-piece, and that 55.5 per cent involved the pin-piece only.

It is only fair to say that these dry flash-over tests are very much in excess of any requirements which were anticipated at the time of the manufacture of these insulators. Had they been tested complete before their first installation, it would have been at a voltage certainly not in excess of 150,000, which is at present considered fairly high for a three-part 60,000-volt insulator. Prior to inaugurating flash-over tests on insulators from the line, some 2,000 insulators in stock were tested to 150,000 volts, 3 minutes, resulting in a loss of 7 per cent, which cannot be considered excessive for an insulator of this shape.

On the top wire where most damage by lightning had occurred in the past, and on the lower wires to the extent necessary to accomplish their insulation, a new type of insulator, shown in Fig. 12, was installed. This is a four-part insulator of about the same outside diameter as the old style three-part insulator, but considerably shorter, 6 inches in fact. It flashes over dry at 190,000 volts, and wet at 105,000 volts. The individual parts and the assembled insulators were tested to dry flash-over voltage for 3 minutes. There was a loss of 3 per cent of assembled insulators by this test.

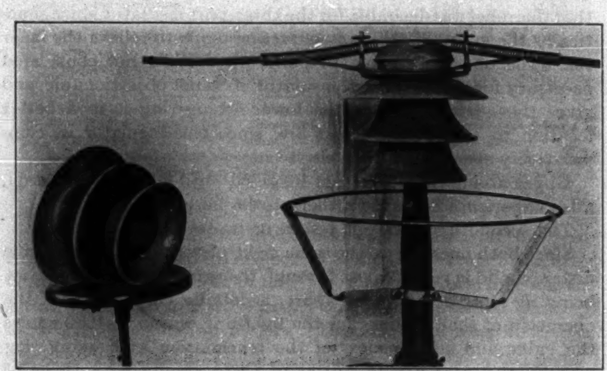


FIG. 12.—New style four-part insulator installed on top wire, 1909 Also shows method of attaching arcing-ring supports to cylindrica pins

An insulator of this design was selected in the light of experience, which clearly indicated that long insulator parts can ill resist the mechanical stress of lightning shocks, and that three thicknesses of porcelain are not sufficient safely to resist puncture in insulators having high flash-over characteristics. Moreover, short shells allow sufficient creepage at high voltage to effect a more nearly uniform distribution of potential upon the several parts, which prevents the puncture of any single shell by a disproportionate division of potential. In short, this four-part insulator was designed to flash over rather than to puncture, and to do this with some margin of safety against puncture.

Lower arcing rings were installed on all insulators in such a manner that relief occurs at a maximum of 160,000 volts, and also in such a manner that wet flash-over values are not reduced. The maximum puncturing potential is thereby limited to approximately 30,000 volts less than the actual voltage which all insulators withstood under test, thus effecting a fair margin of safety against puncture. This result is accomplished by the use of a 26-in. by ⅜-in. iron ring, located approximately 2½ in. above the base of the three-part, and 2 in. below the base of the four-part insulators. It was thought that this relief was desirable for the three-part insulator, since practically the entire 30,000-volt reduction tends to relieve the inner shell, the one most liable to puncture. While not considered necessary for the four-part insulator it is not objectionable, and gives the advantage that the lower arcing ring is in a better location to attract the power arc, since this insulator is, comparatively speaking, a very short one.

Upper arcing rings were not installed until late in the season, after experience had shown them to be necessary.

The second line was not tested or protected in any way.

Since both lines are on the same right-of-way for a considerable distance, and in general pass through the same section of country, being at most a few miles apart, a definite comparison of the operation of the two lines for the lightning season of 1909 shows the value and effectiveness of the reinsulation and arcing ring protection. Also a comparison of these results with those of former years is of interest. It is to be remarked that the line selected for reinsulation is, when on a separate right-of-way, the southerly one, and apparently lies more in the usual path of electric storms than the one which was not reinsulated.

Table I is a comparison of lightning effects on reinsulated and non-reinsulated lines during 1909.

Item 1 shows that one insulator was disabled on the reinsulated lines against 54 disabled on the non-reinsulated lines. Fig. 13 pictures the one insulator lost on the reinsulated line. This is a clear case of breakage by power arc, after flashing over by lightning. It occurred early in the year, before inspection of the work had been made. This failure was due to improper installation of insulator and ring. The 54 insulators disabled on the non-reinsulated lines were destroyed in the same way as were those lost in former years, *viz.*, shattered by lightning, shattered by power arc and punctured.

TABLE I, SHOWING LIGHTNING EFFECTS ON REINSULATED AND NON-REINSULATED LINES, 1909

Reinsulated lines	195 miles, 11,078 insulators.
Non-reinsulated lines	217 miles, 15,121 insulators.

(Reinsulated lines are indicated in Fig. 1.)

Item	Reinsulated lines	Non-reinsulated lines
1. Insulators disabled	1 (*a*)	54
2. Insulators injured (replaced at convenience)	13 (*b*)	36
3. Occasions on which a line was disabled by breakage of one or more insulators	1 (*a*)	15 (*c*)
4. Short circuits or grounds which tripped controlling circuit breakers but did not disable the line	19	12 (*c*)
5. Number of days on which lightning was observed at one or more points on the system	44	44

(*a*) Broken by power arc. Insulator and rings were improperly installed.

(*b*) Nine injured in headpiece by power arc—no neck rings installed. One injured in lower skirts by power arc. Three injured in lower skirts by lightning stresses.

(*c*) Low, on account of practice of removing voltage from 110 miles of non-reinsulated line during lightning, to prevent breakage by power effects, and to obviate attending disturbances.

Item 2 shows that 13 insulators were injured on the reinsulated lines. A careful inspection of these lines was made after lightning storms to determine the exact performance of the arcing rings, and to learn whether or not their location was such as to give the desired results. The results of this inspection are as follows:

Total number of flash-overs found	38
Flashed but not injured	24
Headpiece injured (no upper ring installed)	9
Skirts injured by power arc	1
Skirts injured by lightning	3
Insulators disabled by power arc (improperly installed)	1
Arced to pin before transferring to ring (10, 4-part; 6, 3-part)	16
Arced to ring only 9, 4-part; 12, 3-part)	21
Arced to pin only (4-part insulator destroyed)	1

No insulator was punctured either totally or in any of its parts.

Fig. 14 shows an insulator, protected by a lower arcing ring, which flashed over successfully.

Fig. 15 pictures an insulator, the headpiece of which was broken by a power arc, burning the tie-wire in two. Eight others were affected similarly. No upper arcing rings were installed on any of the insulators which were broken in this manner.

Fig. 16 shows the damage done by lightning stress to a three-part insulator. It had not flashed over. Three were injured in this manner.

Item 3 shows one occasion on the reinsulated line, and 15 on the non-reinsulated line, when the lines were disabled by the failure of one or more insulators. The single failure on the re-insulated line was due to the one insulator appearing in Item 1.

FIG. 13.—Four-part insulator destroyed by power arc. The only insulator disabled on the reinsulated lines 1909

FIG. 14.—Insulator, protected by lower arcing ring, which flashed over successfully

Item 4 shows momentary line interruptions caused by grounds or short-circuits, in which instances the lines were not disabled, but were all right for service at the next application of power, usually within thirty seconds. There were 19 of these interruptions on the reinsulated lines and 12 on the non-reinsulated lines. The fact that there were fewer on the non-reinsulated lines is believed to be due to the operating practice of removing voltage from more than a hundred miles of non-reinsulated line during the known progress of lightning storms in the vicinity of the lines. This was done to obviate damage by power arcs, and to prevent attending disturbances to the system. It is interesting to note that this section of non-reinsulated line was disabled twice while no voltage was on it.

Considering Item 4 in conjunction with the results of line inspection mentioned above, it is evident that the lower arcing ring is not close enough to reduce the degree of insulation of the line under the average conditions of moisture during lightning storms. This is shown by the slight difference in the number of the momentary interruptions on the two lines, and by the fact that on the reinsulated lines in about half the instances the initial discharge was to the insulator pin, and in about half to the arcing ring. At the same time all puncturing of insulators has been eliminated. For these reasons it is believed that the rings have been placed so as to operate as originally intended.

Fig. 15.—Insulator injured in head-piece by power arc. No upper arcing ring was installed

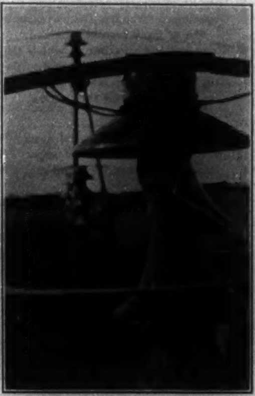


Fig. 16.—Insulator with second shell injured by lightning shock

Item 5 shows the number of days on which lightning was observed at one or more points on the system. This item is interesting in connection with Tables II and III.

Table II is a comparison of lightning effects on the reinsulated lines during 1909, and on the same lines previous to reinsulation during the years 1907 and 1908.

Table III is a comparison of the lightning effects on the non-reinsulated lines of 1909 and on the same lines in 1907 and 1908.

These tables are self explanatory. Attention is called to the extra severity of the lightning season of 1908, and to the fact that the lines which were reinsulated in 1909 had formerly received rougher treatment than had the other lines.

TABLE II, SHOWING LIGHTNING EFFECTS ON REINSULATED LINES DURING 1909, AND ON THE SAME LINES BEFORE REINSULATION DURING 1907 AND 1908

Item	1907	1908	1909
1. Insulators disabled	59 (*a*)	139 (*c*)	1
2. Insulators injured (serviceable)	16	35	13
3. Occasions on which a line was disabled by the breakage of one or more insulators	12	26 (*c*)	1
4. Short-circuits or grounds which tripped controlling circuit-breakers but did not disable the line	32 (*b*)	38 (*c*)	19
5. Number of days on which lightning was observed at one or more points on the system	41	54	44

(*a*) Low, on account of relief gaps.

(*b*) High, on account of relief gaps. This is one-half the total number on the entire system. In addition there were 100 grounds and short-circuits on the system which did not trip circuit-breakers.

(*c*) High, on account of severity of season.

TABLE III, SHOWING LIGHTNING EFFECTS ON THE NON-REINSULATED LINES OF 1909, DURING 1907, 1908 AND 1909

Item	1907	1908	1909
1. Insulators disabled	29	81 (*b*)	54
2. Insulators injured (serviceable)	15	66	36
3. Occasions on which line was disabled by breakage of one or more insulators	9	23 (*b*)	15
4. Short-circuits or grounds which tripped controlling circuit-breakers but did not disable the line	32 (*a*)	42 (*b*)	12 (*c*)
5. Number of days on which lightning was observed at one or more points on the system	41	54	44

(*a*) High, on account of relief gaps. This is one-half total number of entire system. In addition there were 100 grounds or short-circuits on the system which did not trip circuit-breakers.

(*b*) High, on account of severity of season.

(*c*) Low, on account of operating practice of removing voltage from 110 miles of line during lightning storms.

From Table III it appears that lightning effects in 1909 were slightly more than half those in 1908, and somewhat in excess of those in 1907. It is therefore believed that the reinsulated lines have been subjected to a lightning season of average intensity.

Concrete instances may be cited which show definitely that protected insulators have withstood severe lightning. In sections where the lines are 26 ft apart on the same right-of-way, insulators were destroyed on the unprotected line in quantities, and in a manner which indicated extraordinary lightning severity. On the protected line in the same locality insulators flashed over uninjured. On six known occasions all the insulators on a structure discharged, and on six other occasions two insulators per structure were involved. Of the 38 protected insulators which are known to have been affected, 21 were on the lower wires. These results are all indicative of severe lightning effects.

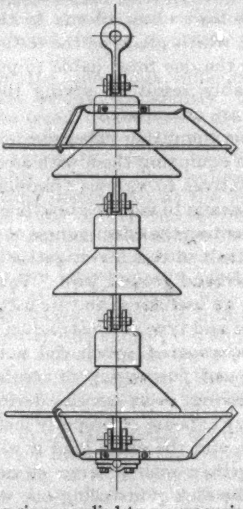


FIG. 17.—Arcing rings applied to a suspension type insulator

This experience with sound insulators protected by arcing rings justifies the feeling that extended interruptions due to line breakdowns by lightning will be very rare in the future, if they do not entirely disappear. Prevention of occasional momentary disturbances, caused by the discharge of one or more conductors to ground from the effects of lightning, is believed to be impossible, since potentials exist at times which are too great to be insulated, and too severely localized to be relieved by lightning arresters at a distance. Duplication or multiplication of circuits controlled by proper automatic sectionalizing apparatus tends to prevent such interruptions from reaching the service.

Virtually no experience has been had with arcing rings on untested insulators. The work of applying them on the remainder of the system, omitting the testing of insulators, is in progress at present. In view of the material protection against puncture which the lower ring affords to the pin-piece of the three-part insulator, which piece, as the testing of 11,000 of these insulators shows, is the one most liable to puncture, and which if saved will probably result in saving the entire insulator, satisfactory results are anticipated.

Before undertaking the rather expensive experiment of reinsulating its lines and equipping them with arcing rings, the company sent representatives to various transmission plants in the United States and Canada to inquire about line troubles in general, and particularly regarding the effectiveness of overhead grounded conductors. The result of this investigation was not altogether favorable to the overhead ground wire. Various opinions were obtained expressing its usefulness and its uselessness. No plant comparable in extent and type of construction with the one under consideration was discovered which did not have to contend with the shattering and puncturing of insulators by lightning, as well as with occasional short-circuits during lightning storms. Considering the heavy expense of properly installing an overhead grounded conductor, and the extra load it would impose on the line structures, together with a large element of uncertainty as to its efficacy, the idea of installing one was abandoned.

While intentionally designed to protect insulators mounted on grounded metal pins it is believed that grounded rings would be beneficial to insulators on wooden pins also.

In view of the extensive use of suspension insulators, some experimental work has been carried on which indicates the necessity for, and effectiveness of, arcing ring protection on this type of insulator. The arrangement shown in Fig. 17 apparently accomplishes the desired results.

DISCUSSION ON "PRACTICAL METHODS OF PROTECTING INSULATORS." CHARLOTTE, MARCH 31, 1910.

President Stillwell: Gentlemen, we have listened to a very interesting paper on a device which I believe is quite new in the art, and original with Mr. Nicholson or his associates; a device that, aside from the results obtained in connection with the plan used in the Niagara Falls construction, will probably be tried in many other instances. At any rate, it appears to me highly suggestive and important in this connection. I believe that if the attention of our designing and operating engineers can be concentrated in respect of overhead transmissions, on the subject of automatic limitation of the destructive effects of a short circuit, results of great value can be accomplished.

I recognize fully the enormous difficulties presented, but they are no greater to-day, apparently, than the analogous difficulties which we faced twelve years ago in connection with underground work, and to-day the underground cable systems are equipped with automatic devices which protect the service so that when a cable fails the only indication of that fact is given by the recording instrument at the power house and the substation. In the case of the Interborough system in New York City, there are, I think, five hundred miles of 3-phase cable in service operating at 11,000 volts. The difficulties that troubled us greatly five years ago are substantially eliminated, and the last time I asked Mr. Scott, who is in charge of the operations of these plants, about his interruptions of service, he said he had forgotten the subject. The records showed they had seven failures of cables during the previous year but not one of them caused an interruption of the service.

In the case of the Southern Power Company, where networks of distribution are being built, it will be possible some day, perhaps even now, to use automatic circuit-breakers in a way which will reduce very materially the commercial interruptions resulting from lightning or other short circuits on the line.

F. P. Catchings: I think in many respects that this paper which Mr. Nicholson has presented this afternoon is one of the most important we have listened to at this meeting. For one reason, particularly, I think so; the problems and difficulties of obtaining the money and financing transmission systems or power plants, and then putting them together, building them after we have obtained the money, you might say are more or less minor difficulties, which we understand and which can be overcome, but the effects of lighting and allied phenomena are rather more obscure, and one of the prime necessities, if not the most important requirement, is to keep these plants in operation —to see that there is a continuity of service. I think the statement in that connection given by Mr. Nicholson sounds the key-note of the whole situation where he says: "No plant comparable in extent and type of construction with the one under consideration was discovered which did not have to contend with the shattering and puncturing of insulators by lightning, as well as with occasional short-circuits during lightning storms." I think that right there, in that paragraph, is a challenge to the electrical engineers of this country, because no matter how much money is invested in the plant and distribution system, unless fairly constant, or nearly constant service can be given, it will not be as successful as it would be otherwise.

The company with which I am connected attacked this problem of insulator puncturing and smashing in a manner similar to that undertaken by Mr. Nicholson, except that we placed the horn gaps on the towers, about 500 feet apart, previously trying the plan of building horn lightning arrester stations every mile or so, and we found, as Mr. Nicholson did, that insulators would puncture on the adjoining tower, within five hundred feet of a five-inch or six-inch gap to earth, so that these discharges and surges were probably of such great frequency that they would not travel 500 ft. of the copper cable, but would discharge through or over an insulator; a horn gap was then placed on every insulator. The line is about fifty miles long, 50,000 volts, Y-connected, and there are some 1,500 of these gaps on the line. They are spaced about five inches, there being approximately 30,000 volts difference of potential between the two horns. We have had the horn gaps on two years or more, and in that time only lost two insulators. One of these was weakened by having been shot with a rifle, so it was not full strength, and the other was punctured through the top. As Mr. Nicholson brought out, it is much more desirable to have momentary fluctuations in voltage or winks of voltage in the line than to have an insulator punctured or smashed and be shut down for several hours. The customers will stand the winks far more readily than they will the shut-down.

There is one question I will ask Mr. Nicholson; is there any drop in voltage caused by the discharge between his arcing-rings?

J. W. Fraser: It seems to me that Mr. Nicholson's solution of this matter is a very good one, and I think you will all agree with me that he has given us something which will be of lasting benefit. He has found a way to protect the insulators, but he has not yet discovered any way of preventing short-circuits.

I was glad to hear our President say that he expects in the next few years to see a distributing system so equipped with automatic circuit-breakers as to be able to cut out lines which were hurt by lightning or in any other manner. I think we need such automatic regulation very much. It has occurred to me several times and has been impressed upon me lately, that the factor of safety in insulators is entirely too small, and I should like very much to hear the opinion of the transmission engineers here in regard to this point. It is customary to use a three-part insulator for 50,000 volts, and a four part insulator for 66,000 volts, and any one who has done any testing on insulators knows that between 50,000 and 60,000 volts, as a rule is all that can be depended upon for one piece of porcelain. It seems reasonable to expect that interruptions could be greatly decreased by increasing the insulation of transmission lines. When we step, say from 50,000 to 100,000 volts, we practically cut the copper to one forth the original area, and we believe that part of this saving could be well invested in insulation. I have been making a rough mental calculation, and I find that doubling the insulation on a 100,000 volt line, increases the entire cost of the whole system about 7.5 per cent. If this extra investment would cut the interruptions in two, the money would certainly be well spent.

E. E. F. Creighton: The protection of insulators is one of the problems that has not received enough attention. It is the most important one in protection at present. The problem of the protection of apparatus against lightning is solved. The information and data given by Mr. Nicholson is of great value.

One thing particularly that needs comment, and needs the assistance of all transmission engineers, is the subject of the spill-over of the power from the insulators, with strokes of lightning, not on the line, but near the line. Mr. Nicholson gave two cases only where the lightning stroke was about a quarter of a mile from the line, that caused flash-overs of the insulators. He gave another case, where the distance, I believe, was seventy feet, on an adjacent telephone line, and that also caused flash-overs. Up to the present time the use of the overhead ground wire is about the only protection advocated for lines of moderate potentials. This particular system has no overhead grounded wire, and it would be a very valuable thing to know whether a stroke as near the line as 70 feet would have caused a spill-over on the insulators if overhead grounded wire had been installed for protection.

It is difficult to get information on this subject, and I would like to suggest one definite method of study—that is by photography. During night storms point a camera in each direction along the lines, at a point as far above the line as possible; change the film after each flash, note whether it causes a flash-over of any of the insulators, and note also by means of station recorders the simultaneous disturbance in the station, especially of the lightning arresters. At the present time there is being put on the market a definite discharge recorder, which will record the exact time when a discharge takes place in a lightning arrester, also tell the phase in which it occurred, and whether it extended to ground or not. It will also give a measure of how long the discharge continued through the lightning arrester and an indication of the current or quantity of electrolyte by the size and nature of holes it bores.

I will ask Mr. Nicholson whether he has any further information of the effect of strokes near the line in causing spill-overs.

If lightning strikes directly on a pole or tower it seems evident that a discharge must take place over an insulator of the power line—even if an overhead grounded wire is used.

J. S. Jenks: My intention is not to discuss this most important paper this afternoon, but rather to give you a few conditions which the West Penn System has overcome and some slight idea of our methods of determining the cause and rectifying same, giving us reasonable protection and practically the same effect that Mr. Nicholson has obtained in his plant.

In the first place we started with the lightning arrester. We made very exhaustive tests and records. We not only recorded the time of each discharge on record sheet, but also the phase and the territory in which the discharge occurred. We have continued this record up to the present time and expect to continue it indefinitely, to a certain extent, in that we keep a record of every arrester which discharges; a record of every storm which occurs and when it reached each portion of the system. We also have a telephonic report from each station on our system telling of the coming of a storm. This places the operating force in position to be ready to manipulate any switches or make any changes in the operation which we think essential.

Our transmission system consists of a loop of 185 miles of line, divided into seventeen sections and fifteen substations. Each section is protected by relief gaps and disconnecting switches as it enters and leaves the substation. Just inside of the substation wall it is protected with a lightning arrester; then it passes to the automatic switch and to the bus. The buses have disconnecting switches in the center, making it possible to divide the system at any point, operating one-half the system from either direction. This makes a flexible method of cutting out any one section that is in trouble.

We experienced trouble from the flashing over of the insulators, where we were protecting railroad crossings with grounded pins and arms, in line with railroad specifications. The majority of our construction is wooden poles, wooden arms and pins, where we have had no trouble from flashing over. We overcame the flash-over troubles by taking a lead from the top of the insulator to one side, letting the discharge go to the grounded arm a safe distance from the insulator. We found this advisable, rather than letting the discharge strike from the line, on account of the trouble we had with aluminum, due to burns. I notice that Mr. Nicholson's experience with aluminum due to burns has been different from ours. We have had numerous lines down—in fact, three cases of trouble before the current was put on the line, due to burns from lightning.

I have brought with me a few samples, which I think some of you may be interested in, showing results of small burns on aluminum wire. We did not test or change the insulators, we obtained our relief without any such expense; as Mr. Nicholson says, it was expected to get relief, from the second line, by simply putting in a discharge gap. I trust the relief will prove satisfactory and justify the risk. The possibility of increased business on the strength of continuity of service is a matter that has been very serious with us. We are in a gas field where we are competing with natural gas sold as low as four cents per 1,000 cu. ft. for power, and twenty-five cents to any person who wants it in the smallest quantity. We have been able to bring our time efficiency—which is based on the effective kilowatt capacity—from about 80.2 up to 99.996. Those last two nines were very hard to get. We have been able to bring it up to this high standard simply by having the automatic devices kept in perfect order, inspected at regular intervals and tested. When we get a case of direct stroke, or something of the kind, we frequently have the section between two substations dropped out of service; we try closing the line breakers; if we get a short-circuit or ground the line is left off and inspected. We have a great many strokes, spill-overs or surges caused by some stroke in the vicinity, which are simply relieved without any interruption whatever.

A word in regard to the factor of safety on insulators. Our transmission carries 25,000 volts. We have, after some little season of experiments, raised our factor of safety higher than the majority of people. We endeavored to get a factor of safety of five on the insulator we used, never putting on an insulator that has a factor of safety less than four. Sometimes the manufacturer will fail to be able to give us five as a straight run, but we compromise and take anything that is not less than four. That is a standard a little higher than most company's.

As to the possibility of direct stroke in the vicinity of lines, we have a record in our office which shows that we had three poles shattered by lightning and knew nothing of it, did not even have a surge. These poles support two three-phase lines, the lines being arranged with the long arm on top, the wires equilaterally placed, and the apex at the bottom. The poles were shattered between two wires only thirty inches apart. So far as we know, that actually happened without even giving a disturbance of voltage. The way we arrived at that conclusion is that our inspectors, who inspect and make records of everything which they find on the line, the condition of every pole and every little chip out of an insulator, etc., inspected the line one day and reported the line in perfect condition; two days following, a very severe storm in the meantime intervening an inspector reported three poles right together which were shattered where the lines crossed over a telephone line. We considered very seriously the matter of overhead ground wires for guarding our line at one time, when we were having the majority of our trouble, but after some experiments with iron wire and fixtures in the coke region where the detrimental effects of the sulphur fumes on the iron wire are prevalent, it was decided to let the grounded wire and fixtures necessary to support the same alone, and go to an increased factor of safety on our insulator, and have some relief gaps for the line.

C. F. Scott: There are two sides to this paper, one that has been presented by Mr. Nicholson, recounting the history of different ways of doing things and results obtained, and another, looking at it from the standpoint of the kind of problem which was presented some two years ago to the transmission company with which he is connected. The conditions are something like this: The company had its important line in service, the insulators were proved inadequate, the exigencies of speed in construction had necessitated putting up insulators without complete tests, and the best thing under the circumstances was probably to do as it did, although it had to take certain chances. It was found then that some of the insulators on these lines, which extended out hundreds of miles, were breaking down. More than that, it was found that when the insulators themselves were possibly in good condition, the conditions were such there would be a flash-over even on a perfect insulator which might destroy the insulator. One of the first requisites was to determine some method of finding the bad insulator, which might be one mile, or ten miles, or fifty miles out on the line, it being almost impossible to see by inspection if they were punctured or not.

The result was the invention of the very elegant method of locating defective insulators described in a paper by Mr. Nicholson before the Institute some two years ago. Now, Mr. Nicholson has pointed out how very difficult it was to make tests of insulators on the line and to replace the poor ones. Different methods were tried, spark gaps were put up at intervals on the upper wire, which was the one which was damaged most often, and yet this proved inadequate. What was to be done? Most of us would condemn the insulators and say that new insulators should be provided, but it was impracticable to get new insulators at once. Mr. Nicholson took the conditions as they were, and in a way which now seems simple, and obvious after you see it, but not before you see it, he made this simple addition for the protection of the insulators, meeting an emergency, which was a very serious commercial condition. It is not a matter for laboratory tests in which it makes but little difference whether the result comes out one way or the other, but it was a very serious emergency condition on a very important transmission line which must be in continuous operation, where the facilities for making tests were very meager. And under these conditions, leaving the insulators as they were, he has devised a method for the protection of these insulators; and the simpler the method the greater the ability required to discover and apply such a method. The idea of putting some kind of a spark gap or lightning rod all around the bottom of an insulator is rather ridiculous when proposed at first, but it is because he has taken that simple and ridiculous thing, and gone ahead and accomplished a notable result that I think marks one of the greatest strokes of ability in the work which he has done.

Most of the pictures of insulators do not look formidable in size, because we have nothing to compare them with, but on one page in Mr. Nicholson's paper we see a piece of an insulator placed alongside of a barrel, and we see that it is about half the size of the barrel. The size here is about the limit, it seems to me, in physical dimensions and weight, which is permissible for the upright pin insulator. As we go to these higher voltages new elements come in which are not found with the little insulators. This matter of flashing over and breaking off petticoats is a thing that has come up in the larger insulators. Again, in the three-part insulator, the distribution of potential within the insulator, which Mr. Nicholson pointed out, becomes a serious matter. The different parts of the insulator, which are cupped one inside the other, do not distribute the voltage uniformly, but the inner part of the insulator, next to the head of pin, probably has to sustain an e.m.f. of twice as much per tenth of an inch, as that toward the outside, and it is a remarkably fortunate thing that the new distribution of potential caused by the placing of the protective rings tends to more nearly equalize the voltage strains throughout the insulator.

As to a minor point, that of the factor of safety, Mr. Frazer thinks that it would be well if we could double the present factor of safety. I wonder if we had insulators which were twice as good as at present whether we would not shift up the 100,000 volts and make it 150,000 volts for the transmission line, and thus tend to retain the present factor of safety. That would be the temptation certainly.

Another question should be asked, and that is how we should measure this factor of safety. Mr. Jenks uses a factor of safety of five; he uses insulators tested at 125,000 volts on a circuit of 25,000 volts. If a 100,000 volt circuit is supplied with 200,000 volt insulator, then there is the same margin of 100,000 volts, although the factor of safety is only two. I think it probable that we may reduce our factor of safety as we go up higher in voltages. Possibly the 100,000-volt margin would be good in one case, and hardly enough in another, but I doubt whether it would be at all expedient to get a factor of safety of four or five by going to 400,000- or 500,000-volt insulators for use on 100,000-volt circuits.

I was interested in what Mr. Creighton said about the recording device for telling what lightning was doing. It certainly does give an excellent insight into the operation of the plant in connection with lightning disturbances to have such records, and it was my pleasure last summer to pass through Montana and spend a day or so at Mr. Gerry's plant, which is the Helena Power Transmission Company, the old Missouri River Power Company. At that plant there is a most excellent record of lightning disturbances recorded putting paper slips in the lightning arrester gaps. They have a number of the multigap arresters, and papers are placed in the gaps next to the line and also in the various shunt circuits and ground circuits. These little telltale papers are taken out from time to time after storms. They give a record showing the results of the discharges in each wire of each line, at each end, and the character of that discharge is indicated by little holes or big ones. The condition is duly recorded on the little slips and the record is transferred to a larger sheet of paper so that one may see the whole record, showing the action on the different lines at each of its ends, and at the different points of each arrester. One can trace down how far the discharge went through the arrester, and where it passed off, and further, he can note the character of the discharge at each place.

I found there that the multi-gap arresters, with shunt resistances, had given such good service that the operating company considered this type as its standard. Electrolytic arresters were being tried but until they had demonstrated their value in service, the multigap arrester which had served efficiently so long were regarded as the standard arrester.

Percy H. Thomas: This is another one of our rare papers, wherein we have a perfectly definite, scientific record of the information obtained from commercial plants that will enable us to draw some conclusions which are almost mathematically definite.

This paper, it seems to me, taken in connection with the paper two or three years ago on the Taylors Falls lightning arrester experiments give us a pretty broad idea of what the transmission engineer has to meet in the protection of lines against lightning.

There are certain definite results and conclusions which we can draw from Mr. Nicholson's paper.

First, when insulators puncture, instead of flashing over, (then perhaps requiring an hour, or even half a day, to get the line into service again), this trouble can be presumably eliminated by the use of the rings proposed by Mr. Nicholson.

Second, where the insulators flash over and are broken by a power arc, the same remedy will apply.

Third, the attack of lightning on the transmission line, as distinguished from the station apparatus, is extremely local. Of this we have abundance of evidence now. One or two poles distance is too far removed from a ground to be at all sure of protecting an insulator.

Fourth, a resistance in the neutral point of the rising transformers may be a great help in maintaining service. I think Mr. Nicholson would probably agree to this statement. Thus grounding of one line is the cause of a much smaller arc than without this resistance, and furthermore the resistance enables the maintenance of voltage on the system, so that reverse-current or overload relays can act while if a dead short-circuit should come on the system, the voltage being entirely removed from the relay, the relay cannot act.

Another point which has not been emphasized, but which is important, is the question of burning that is caused in the transmission line wire by an arc from the pin to the wire. Mr. Nicholson has given illustrated experimental data on this matter, and although I do not suppose it would be safe to draw conclusions from this case for all other cases, yet it gives a definite starting point. Mr. Nicholson fully realizes the fact that although the puncturing of insulators is overcome by the rings momentary interruption of the service is not preventive. Nevertheless the actual operation of the system has been very much benefited by the rings.

It is now very clearly established that insulators can be shattered by lightning alone without current from the generator, and without puncturing the insulator. The petticoats may be shattered without there being a direct puncture to the pin. This is a curious result and this is not the first time it has been brought forward. Presumably a remedy can be found for this condition; it would appear to be a mechanical strengthening, of the petticoats. The exact method will be for the insulator manufacturers to recommend. Ribs on the petticoat might be used, or a heavier petticoat.

Although we have not as yet gotten perfectly continuous service, we can still take a little comfort and not put so much stress on each occurrence of a momentary interruption. There are some classes of service where this is a serious matter, but as power systems go, a wink in the light, or the dropping off of the service for a moment or two, provided it does not occur too often, is not such an overwhelming handicap after all.

I notice Mr. Nicholson has made a study of the reports of various operating companies of the effect of ground wires overhead, and though I do not understand that his report is unfavorable to the ground wire broadly, yet, under the conditions which exist in his plant, he did not think it worth while to try them. I think we still ought to hope that the overhead ground wire will cause a very great decrease in the percentage of interruptions. The critical feature is not so much the mere putting up a ground wire in any convenient location on the pole or tower that may happen to fit a particular structure, but to so install ground wire and to so support and ground and locate it as to give the best opportunity for protecting the line in the light of the conditions to be met as we know them. One condition is the extreme tendency of an induced stroke to side flash when it strikes a ground wire. That means that between towers, on any long span, for instance, a stroke reaching the ground wire, would tend also to spill over on to the transmission wires. Thus, the middle of the span the ground wire should be more widely separated from the conductor than in the towers.

At the latter point where the ground connection is direct to earth, there is not the same necessity for using large spacing. The steel ground wire can usually be strung tighter than the copper wire, and there is often no reason why it should not be drawn above the transmission wire in the middle of the span, the point where the flash-over is most likely to occur.

Two ground wires would be better than one, especially where two transmission lines are on the same set of towers. I think we can safely assume that the attack of lightning is not directly from above; it tends to come from one side or the other and with a single centrally located ground wire may thus first reach the transmission conductor. The use of two ground wires will greatly reduce this tendency.

The cost of the ground wire is a serious item, but under favorable conditions we can erect transmission structures, in which the ground wire shall be an important element of the mechanical stability of the system. In that case, we could perhaps save its cost elsewhere in the system. I will ask Mr. Nicholson if he has any note of any cause of flash-over or puncturing of insulators, other than lightning. There was a time when we used to hear of "internal strains" and other similar troubles in the system, but in recent years we have not heard so much about that sort of trouble.

Mr. Fraser has brought out the fundamental necessity—more margin of safety. We used to have transformers go down frequently. The remedy has been to make better designs and use a larger margin of safety; the troubles with transformers have largely disappeared. If it were possible to do the same thing with high tension insulators, we should certainly be better off.

I feel pretty sure we would have progressed faster in our protection against lightning if that was the only problem we had to think of. The conditions are not at all favorable for the development of protective means. It is very rarely after the original design that in any particular practical case, there is a chance to act intelligently, and carefully and thoughtfully, to lay out a line for protection from lightning. Once in a while there is a company which is large enough to give opportunity for the engineer in charge to make a practical study of the lightning problem, as in the case of Mr. Nicholson's company, and to give an opportunity to try out the result of some method, and if that does not succeed, then to try something else. This is the method of investigation from which we are most likely to get results, as is indeed shown by the present instance.

J. A. Sanford, Jr.: Referring to the statement made by Mr. Scott that he understood that the insulators on Mr. Nicholson's line were rushed in on the line without complete test, using this fact as justification for the loss of insulators by puncture after installation, I think there is one statement in Mr. Nicholson's paper which partially covers this matter and which is better justification for the above loss than the fact above referred to. The statement I refer to is as follows:

"The lesson of the year was not new but showed more forcibly than had been realized before that even if all insulators were capable of resisting puncture, they would continue to be shattered by a power arc following a flash over."

This statement would seem to show that although the manufacturers might have done everything in their power to furnish the best insulators that the art knew at that time, there still would have been a considerable amount of trouble from the breaking of insulators, due to lightning, which loss could only be overcome by the adoption of some protective device as is described in Mr. Nicholson's paper.

Referring to the question of factor of safety, I think that any of the manufacturers who would make a recommendation will recommend an insulator with a reasonable factor of safety, which, hitherto has been a rather flexible quantity, and that the engineer need not have any fear in allowing manufacturers to state what insulator is suitable for a given case, provided full information is furnished with the inquiry stating actual operating voltage, style of construction, and climatic conditions.

With reference to the size of insulator, Mr. Scott brought up the point that some of them were perhaps half the size of a barrel. The largest pin type insulator I know of was furnished to the Edison Company of Los Angeles, being 18 in. in diameter, about 14½ in. high, and this insulator weighed net 43 lb. The largest suspension type units used up to the present time have been made up of two pieces of porcelain, the largest being 14½ in. in diameter and the distance between the point of suspension and the lower petticoat of the insulator being about 10 in.

E. B. Merriam: There are a few points which I wish to mention based on observation of the destructive effects of high-power electric arcs on insulators. A power arc provides a path of low resistance, which on a large system permits a tremendous amount of current to flow, at the same time preventing an abnormal rise in the line voltage, the circuit being opened by protective apparatus. The resistance of these arcs is quite low and might be compared to an equivalent length of No. 0000 copper wire stretched around the insulator. It is the low resistance of this arc which holds the line voltage down until such a time as the circuit can be opened by the line oil circuit-breakers. The size of the arc is not always a measure of its destructiveness as the reflection of the vapors may give the appearance of an arc of great magnitude. A small arc will sometimes cause more trouble than a large one if it is allowed to hold for any appreciable length of time. The time element, therefore, figures quite largely in the amount of damage and burning to the insulator.

The pin insulator, having a petticoat around the insulator pin, is particularly susceptible to the ill effects of heavy power arcs, hence the necessity of protective rings. These petticoats may be broken off one after another on account of the arc "pocketing" and hanging close to the porcelain. The suspension type of insulator, owing to its peculiar construction, has an inherent protection as the arc has a tendency to flare away and extinguish itself. Tests on the suspension type of insulator indicate that protective rings are not necessary. In making tests of this nature it is highly essential that they be made out of doors under operating conditions, as the wind causes the arc to "wander," and the pressure and condition of the atmosphere also have marked effects on the arc, making a laboratory test misleading.

Harris J. Ryan: By practice and investigation that are record breaking for extent of facilities employed and the experience encountered, Mr. Nicholson has advanced greatly our understanding of the related causes that bring about injury and failure of high-tension transmission line insulators. To limit the damaging effects of these causes, he devised and applied to the insulators rings that accomplish their purpose in two fundamental ways:

1. The power arcs that follow a "spill-over" are held free of the insulators.

2. The stray static field set up by the arcing ring is made to crowd the field set up by the skirts of the insulator. For the upright insulator this is so managed that the capacity of the shell next to the pin is considerably diminished. The charge entering such shell from the top of the pin is lessened and the electric stress or pressure gradient there applied is correspondingly lowered. The net result is a more uniform distribution of potential gradient among the several shells along the route of maximum electric strain.

The paper brings up again the principle that pressures are developed on transmission lines at times, that are too high to be withstood by any practical system of insulation and that their effects are localized to such a degree that they cannot be cared for by arresters distributed to a reasonable extent. This and the principle that governs the use of arcing rings have been realized by the author of this paper in a new design of an upright insulator in which enough well-disposed porcelain is used to set the puncture pressure safely above the arc-over pressure. It has been shown that this insulator in combination with arcing rings, has made an important advance in transmission practice.

Mr. Nicholson made tests to determine the destructive effects of power arcs upon transmission lines with and without the use of arcing rings. He found that the arcing rings exercised no material influence in this matter, *i.e.*, they neither increased nor decreased the liability to such damage. In the early part of the paper the author tells us that, "The gaps perfectly protected the insulators containing them". Did they also protect the aluminum cables at corresponding points from damage by power arcs? When a light wind is running, approximately parallel to the line, and a heavy power arc is thereby drawn away from the arcing ring and over the aluminum transmission cable, could not the damage to such cable be prevented by the use of a suitable aluminum guard covering the cable a few feet on either side of the insulator? If required, the power arc at the remote end of such cable guard could be stopped by a barrier of the same metal in the form of a solid disk or an extension piece deflected at right angles to the cable; for the upright insulator, such barrier-piece should be directed downward; for the suspension-type insulator it should be directed upward. Does Mr. Nicholson's experience lead him to consider that guards of this character for protecting aluminum cable are worth what they cost to apply and to maintain? Does his experience lead him to conclude that the transmission cable mounted from suspension-type insulators equipped with arcing rings would or would not be comparatively free from damage by power arcs because of its under-hung position?

Applied to the suspension-type insulator, the arcing rings, by crowding the stray static field about the lower unit, will distribute more evenly the total electric strain among the different units; this should result ultimately in a real advance in the practice that employs this type of insulator.

Irving E. Brooke: The proper protection of high tension transmission lines from injury by lightning or other electrostatic stresses is one of the most important as well as the most difficult problems encountered in the design and construction of transmission lines. The author states that the test on the insulators in question consisted of subjecting each part of the insulator to 75,000 volts for three minutes, but further states that the complete insulator was not tested after assembling. The writer does not understand why the complete insulator was not tested after assembling. In tests of this nature it is not an extreme case when 10 per cent of the tested insulators will break down when subjected to approximately twice the line voltage for which they are intended.

The fact that so many of the insulators fail and puncture is probably due to the design of the insulator, as the potential gradient is such as to subject the top piece or the pin piece of the insulator to a stress greatly in excess of that for which they were designed. This matter of potential gradient for insulators is one that should be thoroughly investigated.

If insulators are made in more than one piece, and although each piece may stand up under the specified test when the several parts of the insulator are cemented together, the distribution of the electrical stress is not the same as if the insulator was one homogeneous mass. When the insulator is made in one piece it is probable that a uniform potential gradient will be secured. As Portland cement is much inferior to porcelain, at the point of contact of the two materials we may have a very abrupt change in the potential gradient or perhaps a re-distribution of the electrical stresses. It has been demonstrated that one piece insulators seldom fail by puncture from operating voltage, but multi-part insulators fail by puncturing one section at a time, which is undoubtedly due to unequal potential distribution.

The subsequent design of the shorter insulator shows a much better type as regards mechanical strength and also an insulator that will withstand approximately the same voltage test.

It is interesting to note that the lightning troubles have been confined entirely to lines themselves and that no trouble has been experienced in stations or substations that could be charged directly to this source. This may be due in a large measure at least to the fact that the steel tower construction with proper station protection provides an easier and more direct path for the relief of high potential charges induced by lightning than that through the station or substation apparatus. The fact that a number of insulators have been broken by a direct stroke may be on account of the so-called lightning-rod effect of the steel tower construction. An insulator could be designed which would flash over before it punctured, but it is hard to foresee which would give better results unless some protection as described by the author were provided to protect the insulator from the power arc after a flash over occurred. The result showing the number of insulators broken on the top wire should be a good guide in the placing of a ground wire on a transmission line.

The question of putting resistances in the neutral connection of the substation transformers is one that is open to argument on account of the possibility of increasing the potential on the line by limiting the current flow to ground.

It has been shown in many instances that a lightning discharge apparently will not always follow the path of lowest resistance. In some instances it has been known to jump several feet at the turn of the wire rather than follow the same wire only a few feet farther, but in a line at an angle to a direct path, to the ground. This may to a certain extent explain the reason why the station and substation apparatus experienced no trouble from lightning discharge. It should also be a good argument for the provision of a ground wire on the transmission line.

In placing the rings around the insulator the author has shortened the air gap, or distance to ground, and while the ground potential is still carried well up inside the insulator it is hard to make the power arc hold from the pin to the conductor.

The log of operation shows some very interesting results. The fact that the circuit breakers were tripped out so many times on the re-insulated line is probably due to the fact that the placing of the arc rings lessened the line insulation and that it brought the ground potential up nearer the conductor.

James Lyman: The author has shown great ingenuity in successfully overcoming the serious effects of lightning discharges over unprotected transmission lines. The method applied will undoubtedly prove of great value to similar situations where the arrangement of insulators on the pole or tower structure does not permit of an overhead grounded cable located well above the transmission conductors.

The value of such a grounded cable in absorbing the high tension charges from clouds and discharges from clouds to ground has been clearly demonstrated by actual experience on many transmission lines. The effectiveness depends, of course, on its being well grounded at frequent intervals, say at every pole or tower structure, and it should be carried well above the line it is to protect. The potential of the earth is thus brought to the level of the grounded cable, and the transmission line is, therefore, removed from the zone of lightning discharges.

If the overhead cable is badly grounded, as, for example, to dry earth or rock, it, of course, offers less protection. In general it is possible to obtain good grounds at small expense. Where good grounds cannot be obtained, as occasionally happens in crossing mountain ranges and rocky country, the author's protecting rings can well be used in addition to the overhead grounded cable.

I believe the overhead cable, grounded as well as conditions will permit, will always offer a very material protection.

Mr. J. B. Foote, engineer for the Grand Rapids-Muskegon Power Company, adopted an original method of protecting the fifty miles of 110,000-volt transmission line, from Croton Dam to Grand Rapids, without an overhead grounded cable, which apparently is entirely effective, for during the year of 1909, not one case of trouble from lightning occurred, although on an older 60,000-volt wooden transmission line a number of interruptions from lightning occurred.

Steel towers are used with an angle iron extension six or eight feet above the upper transmission line acting as a lightning rod. To obtain a good ground the angle iron base extends two feet below the concrete foundation, or a total of six or seven feet into the ground at each corner. The pole line passes through an open farming country where the soil is deep and moist. The line is thus protected by a lightning arrester at each tower or at intervals of from 400 to 500 ft. The suspension type of insulator lends itself well to this construction and wherever steel towers and suspension insulators are used this arrangement might successfully be adopted.

Max H. Collbohm: The method described in Mr. Nicholson's paper is a means to save the insulators from destruction by electrical forces. It does not offer any direct protection to the transmission wires or the station itself. The usefulness of this method is apparent by the fact that if lightning surges are set up either directly or induced in the power wires with a potential high enough to cause arcing over the insulators then a shut-down of the line may result (particularly in a grounded star connected system) without destruction of insulators, thus permitting service to be resumed immediately afterwards, while if this method was not employed the insulators may be destroyed, resulting in a continued interruption of service until the damaged insulators are located and replaced.

The arrangement of the protection rings at about the elevation of the lower petticoat, with a corresponding reduction of sparking distance between conductor and ground, would seem to make it permissible to materially reduce the length of the pin as used at the present thereby increasing its strength.

There is one point in Mr. Nicholson's paper to which I would like to take exception, *viz.*, the statement that it has been found useless to install guard wires over the transmission lines for lightning protection. Although it is true that guard wires do not afford complete protection to the line, they give however at least a reasonable degree of protection if properly installed, *i.e.*, high above the power wires and grounded at every tower. They should furthermore consist of durable non-magnetic material (at least on the outer rim of the conductor) such as found in copper-clad steel wire, and should be at least as strong mechanically as the power wires themselves.

The writer believes that the past failures of guard wires to protect the line are in a great measure due to infrequent grounding and the use of improper material, such as steel. The writer has made some preliminary experiments with high frequency currents which have proved the superiority of copper, or copper-clad steel, over iron as material for grounded guard wires.

G. Semenza: Mr. Nicholson's paper is interesting from two points of view; the statistical one, on one side, as it describes a number of very severe troubles, and studies them in a coordinate way; and the technical one, on the other side, as it proposes a new protecting device which must be considered with the closest interest. Such a device appears to be theoretically effective, and the figures deduced by experience seem to show that it is so in fact.

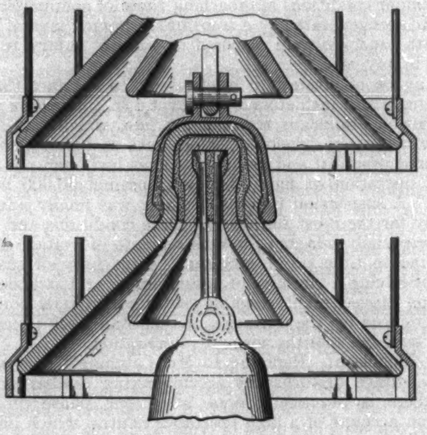
A closer consideration of the figures given, however, discloses some objections which make it desirable to obtain more complete data. First of all, the number of insulators punctured on the old line, both in operation and in the testing room, is considerably in excess of anything heretofore known. The thickness of the porcelain that is punctured in such an insulator ought to stand the testing voltage quite easily, so that, to the writer, the large number of failures would be attributed to imperfect baking of the porcelain.

As to the comparison between the old and the re-insulated line, it is to be noted that while the old line has been left as it was, on the new line 39 per cent of the insulators on the two lower wires, and all of those on the top one, have been replaced with a new and more modern type of insulator. For this reason it is not possible to determine how much of the improvement is due to the re-insulation of the new line.

In a general way it is not apparent how the rings can prevent the puncturing of the insulators. The effect of the rings may be to cause a flash-over to occur more easily than a puncture: such a result may be met by a better proportioning of the parts of the insulators. The protection of the petticoats in case of flash-over must be, on other hand, very effective, as the rings tend to draw the arc out of reach of the porcelain.

I would ask if, in consideration of the slight effects caused by arcs on the cables, it would not be easy to simplify the device by using a single bent wire projecting from the pin and turning upwards to the cable?

J. D. E. Duncan: The paper presented by Mr. Nicholson shows how closely different persons coincide in some cases in the expedients they adopt for the same purpose. The writer has previously developed quite similar arcing rings in connection with high tension insulators devised for use on the Stanislaus installation. One form of these arcing rings shown on a suspension type of insulator is indicated in the diagram shown herewith.



These arcing rings prevent excessive electrical pressure being exerted on any of the insulator elements; where, for example, a portion of the shells or elements has become temporarily ineffective through dust or moisture or where excessive pressure is exerted as in the case of lightning. By surrounding the entire insulator with an arcing ring any arc formed along the surface of the insulator inevitably moves out to the ring through heat and wind action and then the ring itself carries the discharge, the arc then being so far removed from the insulator as not to be dangerous to the porcelain. The rings are arranged so as to have an air space and air circulation around the outer edge of the petticoats so that any heat developed in the rings themselves will not be harmful and as the writer worked up this protective device the rings were mounted on various parts of the insulator structure, such as the petticoats, heads, and other parts.

In theory, the ring is practically a metallic conductor cage arranged around the insulator element and sufficiently removed from it to prevent any contact between the arc formed and the insulator itself, and the arcing distance from the arcing ring to its coöperating arcing points is so arranged as to make this relief path operative before dangerous or puncture voltage is approached. These arcing rings proved entirely effective when tested under conditions approaching those of commercial operation, and arcs generated by a transfor merhaving several hundred kilowatts capacity were disposed of without injury to the insulator in any case.

It may be of interest to briefly refer to the fact that these arcing rings and insulators were devised in connection with the high tension Stanislaus transmission line, which was designed, and the insulators developed, before lines at 100,000 volts were considered practical and before any lines had been put in commercial operation at more than the nominal 60,000 volts potential. A suspension type of insulator was finally adopted as being by far the most suitable for these conditions and because it was especially adapted for such increase of voltage as might from time to time prove necessary. This form of suspension insulator having a plurality of nested domes and attached petticoats has proved highly reliable under commercial conditions, as is evidenced by the operation of this Stanislaus transmission line for over ten months without interruption.

L. C. Nicholson: Replying to Mr. Catching's question concerning voltage disturbances accompanying discharges to the rings, there is practically none when one phase discharges. This is on account of a high resistance neutral which limits the current flow to about 30 amperes. Voltage disturbances accompanying simultaneous discharges on two or more phases are very great; in fact, under such short-circuit conditions there is practically no voltage anywhere.

Mr. Creighton asks for concrete cases of lightning stroke at various distances from the lines, and the corresponding effects upon the line. I regret that we have no very considerable data on this point. I have ventured to make a statement which indicates how we feel about it—less than 500 feet away is very dangerous, more than 3000 feet away fairly safe. Various observations made from time to time seem to indicate these general limits. Causes other than lightning which may produce flashovers are few. Opening a long section of unloaded line by means of open-air disconnecting switches sometimes sets up surges which cause flash-overs. The accidental grounding of one phase as by a tree branch or other object, lightning arrester discharge, etc., may cause flash-overs to occur on another phase at another point on the line, due to the sudden re-arrangement of the electrostatic conditions of the system. Surges produced in this manner frequently reach very high values.

I agree with Mr. Thomas that insulators may be shattered completely by pure lightning effects, unaccompanied by puncture or power. I think he is also correct in that the attack of lightning is frequently from the side instead of from above. I have a case in mind where two east and west parallel lines twenty six feet apart, insulated in the same manner suffered very unequally from lightning, the south line sustaining practically the entire damage, the north line being nearly immune. In this case the storms approached from the southwest.

As to the length of time necessary to injure an insulator by a large arc, a perceptible time is required, though very slight, perhaps about one quarter second, with a 10,000-kw. arc.

Mr. Ryan suggests the use of a metal disk on the cable to prevent the arc travelling out beyond the unprotected portion of the cable. We have experimented with this and other equivalent arrangements, but have not found anything that will deter the arc. In fact any obstacle on the cable appears to be objectionable since it furnishes a shielded zone in the lee of which the arc may rest and accomplish considerable burning.

Protection by a sleeve or serving of small wire would be entirely effective provided such protection extended far enough along the cable. However, such protection would necessarily extend, say, 50 feet each way from the insulator, since frequently arcs travel this distance along the wire. Two cases are on record where the arc extended from the lower ring to a point on the cable 250 feet from the insulator. If the passage of the arc along the cable is unobstructed, the burning is not serious. Twelve cases occurred in the season of 1909 in which the cables were blistered for from 5 to 50 feet. No cable was burned seriously enough to warrant repairing. Our conclusion is that the cable should be bare, so as to allow the arc to travel readily along it, which action forestalls serious burning at any one point.

In the case of suspension insulators, protected by rings, burning of the cable cannot occur since it is impossible for the arc to come in contact with it.

Something has been said about automatically sectionalizing parallel lines in case of a ground on short-circuit on one of them. We have found it entirely feasible to cut out a grounded line automatically by the use of a specially constructed relay. However, short-circuit, low-voltage conditions are very hard to treat, and while some progress has been made with automatic devices they are at present considered far from satisfactory.

As to the efficiency of an overhead ground wire in protecting against lightning, several gentlemen seem to construe my remarks on this subject as being entirely unfavorable to the use of a ground wire. Such was not intended, and our reasons for not installing such protection are as stated, *viz.*, the heavy expense incident to properly installing it on structures such as ours, already built, together with the extra load such wire or wires placed well up above the line would impose; and, as a result of an extensive canvass we concluded that the benefits to be derived from such protection were far from ideal and did not warrant the expense. We were looking for something better and less expensive than the overhead ground wire. It may be that it takes overhead ground wires, arcing rings, suspension insulators, and more, to eliminate all lightning trouble.

Mr. Brooke concludes from the log that the reason the reinsulated line tripped out so many times is due to the fact that the placing of the arcing rings lessened the line insulation and brought ground potential up nearer the conductor. We interpret the operating results differently. For example, considering the 38 cases of flashover found upon inspecting the reinsulated line, tabulated on page 261, 17 were complete flashovers to the pin, and consequently the entire insulation of the line was developed. Moreover there were two-thirds as many trip-outs on the old line as on the reinsulated line, and in addition there were 15 instances of disablement on the old line. Assuming approximately the same amount of lightning on the two lines, the reinsulated line shows 20 trip-outs against 27 on the old line. I call attention here to an observation omitted in the paper, *viz*, in only three cases of the thirty-eight inspected was the initial discharge vertically downward from the cable to the ring. In thirty-five cases the discharge emanated from the tie wire in the neck of the insulator, either to the pin or to the ring. Our conclusion is that under average conditions of moisture on the insulator surface during storms the rings are not close enough to reduce the degree of line insulation. It is entirely feasible to lower the ring so as to develop the full dry flashover value of the insulator, in which location the ring is equally effective in taking the power arc off the pin.

Mr. Semenza's opinion that insulators should be designed so as to flash-over before they are punctured is entirely concurred in. This is what we have attempted to get in the new style four-part insulator. On the other hand, given any insulator, it is possible by a ring to reduce its dry flashover value to a point comparable to its puncture strength, and at the same time keep the wet flashover value normal. There is, moreover, no great objection from an operating standpoint to doing this. This is what we have done with the old type insulator.

As to replacing the ring by a gap from the cable to a single bent wire, leading upward from the base of the pin, this would be equally as effective as a ring, but for only one condition of wind direction. An insulator flashes over on its wettest side, which is the windward side, in a lightning and rain storm. Were the proposed gap set at a value less than wet flashover so as to attract all flashovers (wet and dry) two objections arise; first, the degree of line insulation is reduced and, second, under certain wind directions the arc would attack the pin and destroy the insulator. A continuous metal ring enables the arc to shift readily around the insulator and to accommodate itself to all wind directions, and always to the leeward of the insulator. A horizontal gap at the top of the insulator, if set below wet flashover value, will prevent injury to insulators by power arcs, but such gaps are more difficult to construct and if set close enough to prevent insulator "spill-overs" are a menace to operation. Our experience with gaps of this nature indicates that it is impossible to adjust and to keep in adjustment a large number of them.

I wish here to add some data which shows the effect of the lower ring to reduce the puncturing tendency of the three-part insulators. We recently had occasion to test 800 of these insulators, first with the ring in place and then with the ring removed, the voltage in each case being sufficient to cause flashovers, *viz.*, 160,000 with the ring and 195,000 without the ring.

Failures with ring........................	3 per cent
Failures without ring......................	22 per cent

Of the 3 per cent failures with ring, only 1.25 per cent was due to failure of the pin-piece, whereas of the 22 per cent failures without the ring, 17 per cent was due to the failure of the pin piece.

Mr. Duncan proposes the use of metallic rings supported on the insulator parts. I understand from his remarks that this device was developed experimentally, with small amounts of power. Several years ago an arrangement such as this was proposed for our insulators, but subsequent tests showed it to be entirely without effect when large amounts of power, say, 10,000 kw. and over, are put into the arc. Since the damage to the insulator is caused by the lower terminal of the arc running up the pin, the only cure is to take the arc off the pin automatically and immediately after its formation. So long as this is not accomplished, the insulator will be destroyed. Experiments show that the attenuated portion of a large power arc approximately eight inches and more away from its termini is not destructive to porcelain even though in continuous actual contact therewith. For this reason little good is accomplished by "short-circuiting" the arc as it passes the edge of the insulator skirts, while allowing its terminal to remain on the pin of an upright insulator or the metallic links of a suspension insulator. Furthermore a very slight breeze causes the body of the arc to flare clear of the insulator skirts, even with conducting bands about them, which action prevents the metal bands from performing any function. There is no reason why the arrangement mentioned will not limit the puncture stresses to any desired amount.

The operating results given in the paper would hardly be complete without referring to our Waterloo of 1910, when two insulators on the reinsulated line were exploded by what appears to have been a direct stroke of lightning. A number of other insulators on adjacent structures flashed over, but were uninjured. This incident shows that there is a degree of lightning which is fatal to protected insulators, but from past experience we know that such occurrences are very rare.

During another storm of 1910, the telephone line 100 feet from the power line was struck and several poles splintered. Flash-overs occurred at that point on the power line, but no insulators were damaged. This result indicates that the line is practically proof against breakage by anything less than a direct stroke.

The general bearing of this situation it seems to me is this—we have transmission lines which will operate practically without extended interruption, but with a number of momentary interruptions during the season, momentary short circuits, I should say, which are sufficient to throw out of step the present type of synchronous receiving apparatus on the system. I believe the results point to the necessity for the design and the use of synchronous apparatus, which will suffer heavier disturbances of voltage than the present type can withstand.

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MOTOR APPLICATION TO MACHINE TOOLS

BY CHARLES FAIR

The subject of motor application to machine tools is rather a difficult one to treat satisfactorily in an abstract way. However, in this paper I shall try to point out the fundamental principles underlying motor applications to machine tools and trust that these will aid, not only in the selection of the proper motor and control, but in their application to machine tools as well. Observing these principles will have a marked effect upon production and will reduce maintenance to a minimum.

Since much has been written on the advantages of motor-driven tools, it will suffice here to mention briefly only a few; such as sanitation, unobstructed light, absence of belts and belt troubles, head room for cranes, hoists, etc., elasticity of arrangement, ease of adding new tools and of moving and rearranging tools, close speed regulation, greater power and overload capacity, maximum output of tools, power transmission, facility for running only such tools as are required for overtime work, and finally, under modern structural conditions, avoidance of the well-understood difficulties of line shaft installations in cement buildings. These points are admirably illustrated in the following photographs.

Figs. 1 and 1a are views showing the interior of a machine shop of a large manufacturing company. As this is one of the largest buildings ever built to be used exclusively as a machine shop, it would probably not be amiss to give here a brief description of the building and the machines.

The building is 295 ft. wide and 800 ft. long. The total floor space of the building, including galleries is 490,000 sq. ft. or 11.2 acres. It contains 997 machine tools operated by 1047

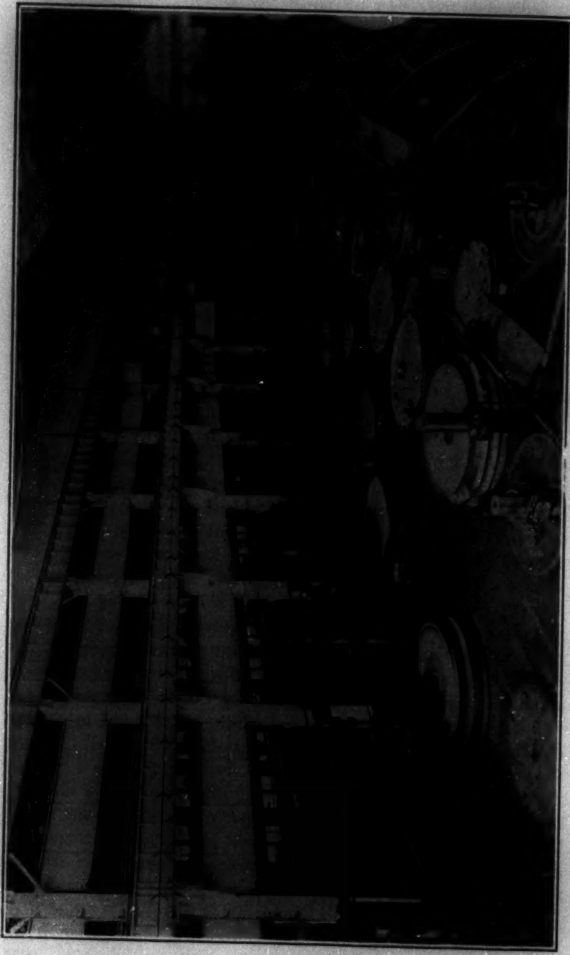


Fig. 1

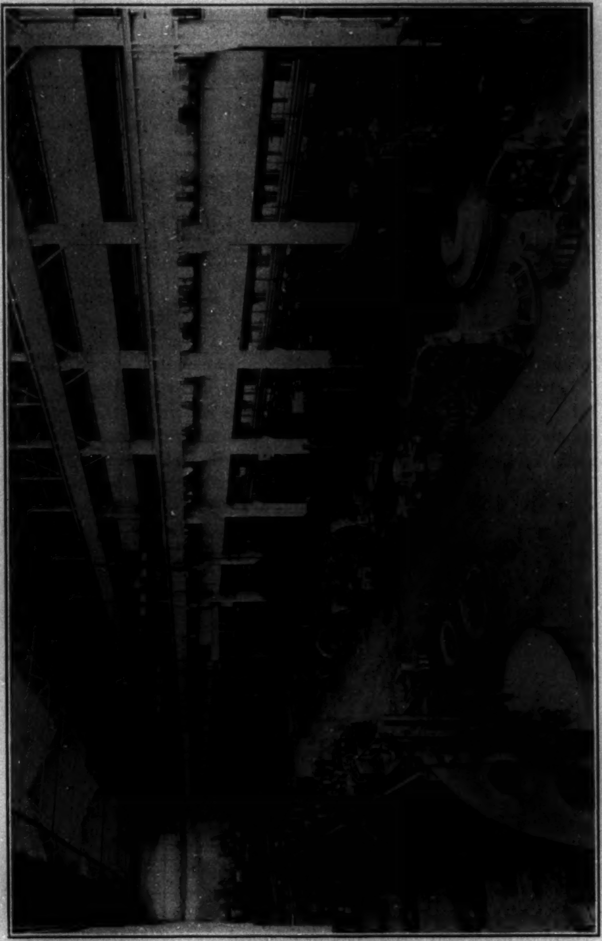


FIG. 1a

motors, 941 of the tools being driven by independent motors, and a number of them requiring two or more motors. There are 56 of the smaller tools, all of which are located in the second gallery, which are arranged in groups varying from six to twelve tools per group. The machines range in size from a 40-ft. boring mill down, there being 51 boring mills 6 ft. and over, and 36 portable tools used on the iron floors. This large number of tools requires for handling work, 35 cranes ranging from 5 to 50 tons and 8 electric hoists, as well as 8 freight elevators and 2 gantry cranes.

Fig. 2 is a very good illustration of the overhead clearance due to the use of individual motors and shows a number of 8-ft. boring mills. Each of these mills is driven by a 20-h.p. adjustable-speed motor, the cross-rail being raised and lowered by a 3-h.p. motor. The controllers for operating both motors are shown fastened to a bracket which in turn is bolted to the machine. These machines are placed under a gallery, as shown in the illustration, as also are the boring mills shown in Fig. 3. The latter are placed directly behind those shown in the previous illustration, thus making a very compact arrangement of tools and at the same time allowing plenty of room for handling work. Except in the case of the first mill on the left, the controllers for operating this group of boring mills are arranged as shown on the first mill on the right.

Fig. 4 is a view of another building looking down the center aisle of the second floor. This shop is a modern reenforced concrete building in which no line shafting whatever is used, even though the majority of the tools are old ones changed over to individual motor drive. Although many of these tools require short belts, this is a very different matter from belting from lineshaft to countershaft and from countershaft to tool.

Fig. 5 shows a group of lathes driven by individual motors. If this group of lathes were belt-driven and arranged as compactly as shown, with two belts from line to countershaft, the ceiling would be literally a mass of belts.

Fig. 6 shows a punch press department. All the punches and shears in this building are individually driven by alternating-current motors, although such tools are also frequently driven by direct-current motors.

Up to comparatively few years ago in the majority of the shops where motors were used, they were simply belted to the lineshaft or countershaft of the tool. Adjustable-speed motors were not so commonly used then as now, nor were they made in the great variety of sizes and speeds now obtainable. Today, especially in the case of new tools with their requirements of higher power

FIG. 2

and closer speed regulation, due to the use of high-speed steel, it becomes not only more convenient, but in many cases almost a necessity, to apply the motor directly to the tool.

FIG. 3

When the work of actually equipping a factory with motor drives is undertaken, it will be necessary to study the conditions of operation, which vary greatly with the product manufactured,

FIG. 4

FIG. 5

and while in some cases these conditions are comparatively simple in others they are more complex. The arrangement of tools will to a large extent depend upon the nature of the work, and as to whether alternating or direct current is available; it will also depend upon whether the convenience of operation and handling of material are of sufficient importance to call for a considerable number of individual drives, or as to whether it is to be generally a group-driven shop.

In driving tools with individual motors it will be remembered that the motor not only supplies the power and speeds best adapted to the tool, but that the speed of the motor alone in many cases covers the entire speed range of the tool, and that the motor can be applied directly to the tool, making a compact unit.

Fig. 6

When equipping tools with individual drives, the controlling apparatus as well as the motor should be attached directly to the tool when possible. This arrangement allows moving the tool by simply disconnecting the leads and connecting them in the new position. In the case of portable tools this, of course, is an absolute necessity.

A graphic recording wattmeter in circuit with a tool not only tells the actual power consumed by the machine, but also shows whether the tool is operating at its maximum rate, by registering the time of unproductive cycles or the length of time the tool is idle; and by analysis, the cause of the lost time may be discovered and result in a change of conditions with a corresponding increase in production. Poor lineshaft alignments have been detected by watching the integrating wattmeter. Many shops are paying dearly for lack of attention to alignment of shafts, etc.

Difficulties concerning the choice of the type of motors for tools have been considerably exaggerated. The following table will, in a general way, aid in the choice of motors. The great variety and the sizes of tools of the same name make it necessary in a general list, such as this to double-check a number of tools.

MOTORS FOR MACHINE TOOLS

Tool	Direct current			Alternating current		
	Shunt	Comp.	Series	×	‡	✱
Bolt cutter	†			×		
Bolt and rivet header		20% 40%		×	‡	
Bulldozers		20% 40%		×	‡	
Boring machines	†			×		
Boring mills	†			×		
Raising and lowering cross rails on boring mills and planers		60%	†		‡	
Boring bars	†			×		
Bending machines		20% 40%		×	‡	
Bending rolls		40% 80%	†			✱
Corrugating rolls		20% 40%		×	‡	
Centering machines	†			×		
Chucking machines	†			×		
Boring, milling and drilling machines	†			×		
Drill, radial	†			×		
Drill press	†			×		
Grinder—tool, etc	†			×		
Grinder—castings		20%		×		
Gear cutters	†	20%		×		
Hammers—drop		20% 30%			‡	
Keyseater—milling—broach	†			×		
Keyseater—reciprocating	†	20%		×		
Lathes	†			×		✱✤
Lathe carriages			†		‡	
Milling machines	†			×		

MOTORS FOR MACHINE TOOLS—(Continued)

Tool	Direct current			Alternating current		
	Shunt	Comp.	Series	×	ǂ	✱
Heavy slab milling	†	20%		×		
Pipe cutters	†			×		
Punch presses		20% 40%		×	ǂ	
Planers		20%		×	ǂ	
Planers—rotary	†	20%		×		
Saw—small circular	†			×		
Saw—cold bar and I beam	†	20%		×		
Saw—hot		20%		×		
Screw machine	†			×		
Shapers	†	20%		×		
Shears		20% 40%		×	ǂ	
Slotters	†	20%		×		
Swaging		20%		×	ǂ	
Tappers	†			×		
Tumbling barrels or mills		20%		×		

× Squirrel cage rotor.
ǂ Squirrel cage rotor-high starting torque.
✱ Slip ring induction motor with external rotor resistance.
† Might be used for tire lathes as it allows slowing down when cutting hard spots.

It must be kept in mind, however, that various circumstances, such as size or roughness of work, flywheel capacity, etc., may call for radical departures in choice of motors, this list being compiled to meet average conditions. Shunt motors, for instance, are used in the following cases; when the work is of a fairly steady nature; when considerable range of adjustment of speed is required, as on lathes and boring mills; and on group and lineshaft drives, etc.

Compound-wound motors are used where there are sudden calls for excessive power of short duration, as on planers, punch presses, etc.

Series motors should be used where speed regulation is not essential and where excessive starting torque and slow starting speeds are required; as, for instance, in moving carriages of large lathes, in raising and lowering the cross rails of planers and boring mills, and for operating cranes.

When in doubt as to the choice of compound or series motors of small horse power, the choice might be determined by the simplicity of control in favor of the series motor. Series motors, however, should never be used when the motor can run without load, as the speed would accelerate beyond the point of safety.

The alternating current motor of the squirrel cage rotor type corresponds to the constant-speed, shunt, direct-current motor, but with a high-resistance rotor it approaches more closely the characteristics of a compound direct-current motor. It is understood that the variable-speed machines, checked in this list under the alternating-current squirrel cage rotor column, have the necessary mechanical speed changes.

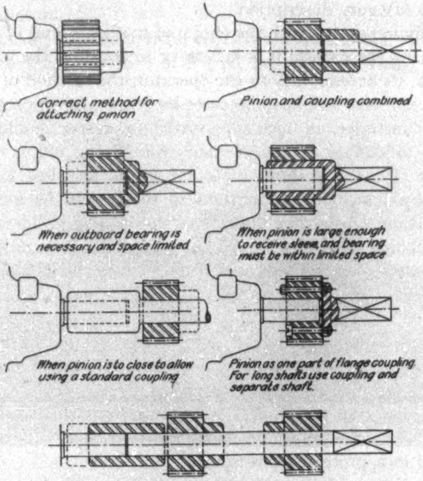
The slip-ring induction motor with external rotor resistance would be used for variable speed, but this must not be construed to mean that it corresponds to a direct-current, adjustable-speed motor, as it has the characteristics of a direct-current shunt motor with armature control.

The self-contained, rotor resistance type would be used for lineshaft drives, and for groups when of sufficient size.

Multi-speed, alternating-current motors are those giving a number of definite speeds, usually 600 and 1200 or 600, 900, 1200 and 1800 rev. per min., and are made for both constant horse power and constant torque. These motors would be used where alternating current only was available, or direct current limited; and the speed range of the motor, together with one or two change gears, would give the required speeds.

One of the most important features in the selection of motors and one that is persistently overlooked, is the strict adherence to the use of standard motors, and by standard motors is meant standard armature shafts as well. The importance of maintaining standard armature shafts will be readily recognized by the factory management when it is pointed out that by such an arrangement spare armatures are reduced to a minimum, and that in an emergency it is possible, where these are not carried, to replace an armature or even a whole motor, from an idle tool, or from a tool of relatively less importance at the time. Also, of course, stock motors can be supplied promptly by the manufacturer and shipments materially improved if special shaft extensions are not called for. That special features in a motor are sometimes desirable, is not to be denied; it may so happen that the advantages from some special feature in the motor may more than offset the disadvantages above referred to, but in cases where these features are thought necessary they should be carefully considered before final decision.

The sketches in Fig. 7 show a number of arrangements used in order to maintain standard motor shafts. In addition to these, many forms of flange and split couplings are used. The method which is selected for connecting standard shafts will depend upon the conditions surrounding the drive under consideration. Tools which only a few years ago were equipped with special motors are today driven by standard motors, and as a result are easily and quickly repaired. In the early days of the motor drive many special features were thought necessary in the motor to make it adaptable to the tool; special frames, shafts and speeds were required by the tool builder, and little thought was given to the interchangeability of parts. It is therefore easy to recognize in these early equipments responsibility for the existing idea that special features in the motor are still necessary for tool equipments. Many of these features are now recognized as unnecessary, and today the tool builder in many instances builds his tools ready for attaching standard motors.



Correct method for attaching pinion

Pinion and coupling combined

When outboard bearing is necessary and space limited

When pinion is large enough to receive sleeve and bearing must be within limited space

When pinion is to close to allow using a standard coupling

Pinion as one part of flange coupling. For long shafts use coupling and separate shaft.

Standard sleeve coupling

FIG. 7.—Some methods used to maintain standard motor shafts for the interchanging of armatures

At the present time, so far as tools are concerned, we think of the motor largely as a means of driving the tool and not of the possibilities of the motor becoming the main element of the tool construction. Here again, high-speed steels, together with the improvements made in the motor, will produce many new designs in tools with corresponding higher efficiencies.

The old prejudice existing against the electric motor, which was mostly a mistrust due to a lack of familiarity with its operation, is rapidly dying out, and today motors are found driving machines in shops of every description.

Equally important with the choice of motors is that of control. In selecting the control it is necessary to consider the nature of the work, its accessibility to the operator, the method of attaching it to the tool and in some cases its relative position to other tools; for instance, an open type starting rheostat should not be exposed to danger of short-circuit from flying chips. In the majority of cases, a shunt motor of ¾ h.p. and less would be started by a switch. Exceptions to this would be motors on tools that must be gotten under way slowly, and grinders driven by direct-current motors for reasons of safety. With adjustable-speed motors, care should be taken to throw the switch on full field. Series motors up to 8 h.p. or even larger can be started by switch. Exceptions to this would be cranes and tools requiring a certain amount of armature speed regulation. Larger motors, for tools where starting service is infrequent or not severe, and for lineshafts and for group drives, would be satisfactorily operated with a dial type controller, which is cheaper than the drum controller, provided, however, that the controller is placed in a protected position.

When making the installation, accessibility to the controller in case of accident should be kept in mind, even though of little importance so far as starting up is concerned. The starting apparatus should be placed where the motor or some of the moving parts can be seen by the operator. On individual motor-driven tools, where the motor is started and stopped many times a day or where the starting conditions are of a severe nature, or where tools are edged along, drum type controllers with extra heavy starting resistance should be used. For adjustable-speed motors, using the drum type control, the field control should be through fingers making contact on segments of the controller drum and not by sliding contacts on a dial, as with the latter, trouble will develop sooner or later. Motors above 40 or 50 h.p., under these severe conditions, are best operated by a master controller which operates contactors for cutting out steps of starting resistance, and if adjustable-speed, the field control should be taken care of, as stated above, by fingers making contact on segments of the drum. This class of starting apparatus will stand any quantity of abuse and, by the addition of a simple current limit relay device, becomes practically a fool-proof protection for the motor. There are cases where it might be advantageous to use master controllers and contactors even with smaller motors.

Alternating-current squirrel cage rotor type motors, two-phase and three-phase, up to 5 or 8 h.p., generally speaking, can be

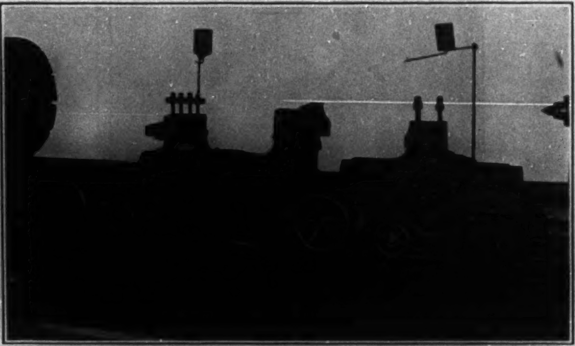


FIG. 8

thrown on the line, depending largely upon power conditions. Above 5 or 8 h.p. they should be operated by compensators. The self-contained rotor-resistance type would be started by a sliding resistance in the rotor, and the slip-ring type by a controller with external resistance.

Upon the convenient arrangement of the control depends, to a considerable degree, the output of the tool, and the importance of the arrangement from the standpoint of the operator cannot be ignored, since the output of a tool will be materially increased when an operator can start and stop the tool and obtain at all times maximum cutting speeds by simply turning a handle. The controller must be placed in a safe position and should be accessible for repairs, which very often means that some arrangement is necessary to bring the operating handle within easy access of the operator. A familiar illustration of the convenience of control is the arrangement so commonly seen on lathes, whereby the operating handle travels with the tool carriage and allows the operator at all times a complete control of his tool. The motor and control for moving lathe carriages is perhaps not quite so familiar; such an arrangement is shown in Fig. 8, which shows a 60-in. lathe, the main drive being a 35-h.p. 635/1270-rev. per min. motor and the carriages being operated by a 3½-h.p.

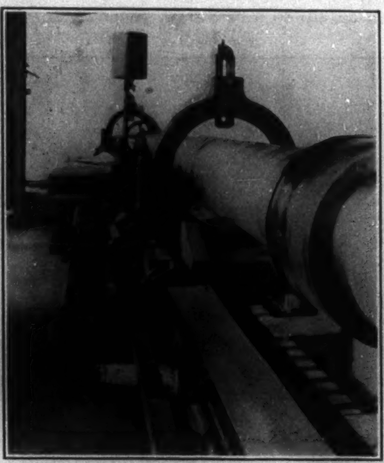


FIG. 9

series motors, while Fig. 9 shows the method of fastening and protecting the trolley for operating the motors on the lathe carriages. The latter illustration shows a 42-in. lathe, and was selected because in addition to the regular method of fastening the trolley it shows the change necessary in the supporting brackets if taper attachment be used. Strange as it may seem, this most important feature, the convenience of control, which bears directly on production, is ignored in the majority of the tools where the control is of the greatest importance. This convenient arrangement of control is shown in the following illustrations

Fig. 10 shows an 8-ft. boring mill, driven by a 20-h.p., 600/1200-rev. per min. adjustable-speed motor. The cross-rail is raised and lowered by a 3-h.p. motor. It was a very easy matter in this case to place the controllers in the most accessible position for the operator by fastening them to a bracket which in turn is bolted to the machine. Boring mills on which it is not convenient to have the controller placed as shown in Fig. 10, might be arranged as in Fig. 3, previously shown, which calls for an extension of the controller shaft, a coupling, a bearing bracket and an operating wheel; or again as in Fig. 11, which shows the arrangement of control on a 16–25-ft. boring mill, which is operated much as the one shown above but with the addition of a universal joint. This mill is driven by a 50-h.p., 500/1000-rev. per min. adjustable-speed motor, and two 15-h.p. constant-speed auxiliary motors.

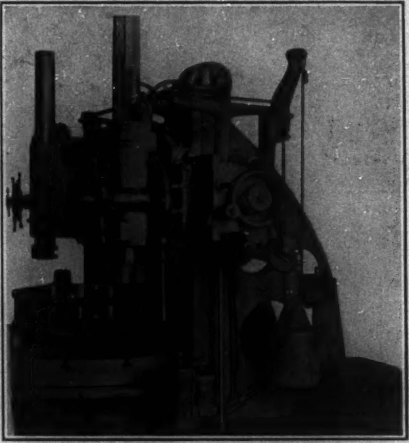


FIG. 10

In the case of the vertical milling machine shown in Fig. 12, it was desirable to provide two positions for the control—one that at all times could be operated from the floor line, and one traveling with the cutters, which at times might be ten feet or

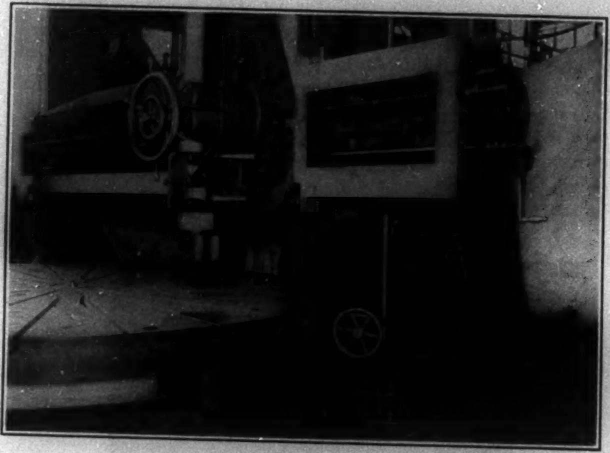


Fig. 11

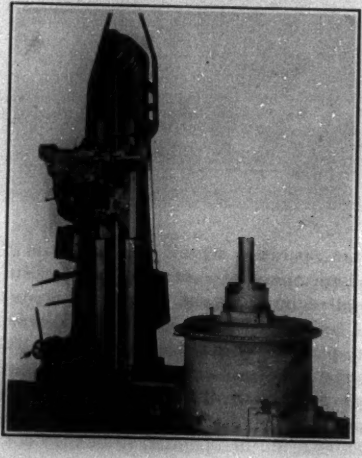


Fig. 12

more from the floor. On account of the limited space for the controller it was necessary, in order to bring the operating wheel in the proper position for the operator, to use spur gears, universal joint, and bevel gears.

Fig. 13 shows a vertical milling machine, driven by a 7½ h.p., constant-speed motor, and shows clearly the operating wheel together with the safety latch which drops in place when the controller is brought to the off position.

On slotters it is often necessary to put the controller on the left side of the tool with the operating handle on the right, as shown in the case of a 12-in. slotter, Fig. 14, driven by a 5-h.p., 500/1500-rev. per min., adjustable-speed motor.

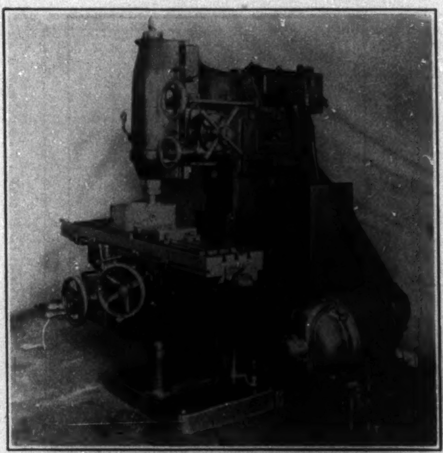


Fig. 13

Fig. 15 is a 60-in. slotter, driven by a 20-h.p., 890/1330-rev. per min., adjustable-speed motor through pneumatic clutches, and for moving the table a 3-h.p. motor is used. Two controlling stations were necessary on this machine, the work at times being so large that it was not practicable to operate the front wheel, yet for the majority of the work it was the most satisfactory position. The safety latch for the off position is clearly shown on the operating wheel. The controller is seen on the rear of the machine.

In the case of the milling machine driven by a 5-h.p., 500/1500-rev. per min., adjustable-speed motor, shown in Fig. 16, it was at times, on account of the nature of the work, essential that the operating handle be placed in the position shown.

Fig. 17 shows the motor and controller travelling with the head of an 84-in. rotary planer, driven by a 15-h.p., constant-speed motor, the current being received through sliding contact which is on the rear of the machine and is completely enclosed.

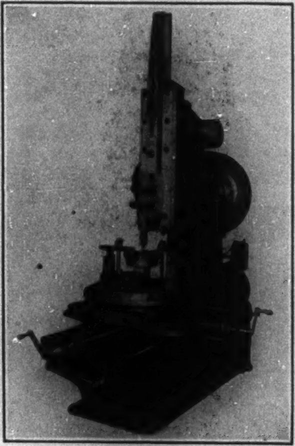


Fig. 14

The controller is placed under the platform, while the controller handle is brought out at the top of the pedestal as shown.

The horse power required for driving tools calls for the exercise of considerable judgment, especially in the case of alternating current motors where power factor enters into consideration. Exhaustive tests have been made to determine the amount of power required to drive tools, but it is to be regretted that many of these tests are lacking in essential features that would make them valuable. Conclusions drawn from incomplete data are apt to be misleading; as in the case of tests made with motors which are considerably underloaded or overloaded, and where efficiencies are not taken into consideration; or where the material used and duration of test are not stated; or where there has been failure to state whether the test was a practical one or merely a breakdown test. The conclusions drawn from breakdown tests are often deceptive and should not be used for determining power to drive tools; also it does not follow that a tool which stands up longer than another under breakdown conditions, will do the same under practical conditions. The majority of the formulas now in existence for computing horse power required for tools are generally misleading and useless, and no general formula that would be of practical value has been developed, as the power required varies with the metal worked, the cutting speed and many other conditions.

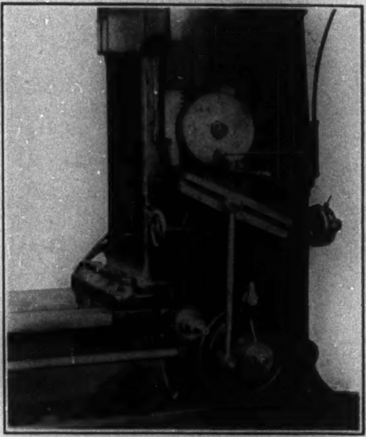


Fig. 15

The construction of the tool is seldom taken into consideration when estimating horse power, yet some of the worm-driven tools are notoriously inefficient. Other tools are so constructed that the greatest part of the power delivered to the tool is consumed in friction losses and not in useful work; again, the tool may be constructed upon approved lines but may not be stiff enough to stand the strains to which it is subjected, thereby causing considerable loss of power, all of which, as well as the difference in power due simply to the shape of a cutting tool, has been repeatedly proved by tests. In one instance, it required 72 per cent more power to drive a plain spiral milling cutter than the same cutter nicked.

The advent of the high-speed steel and the high-power tools, together with the increased speed of old tools, makes much of the data bearing on horse power collected up to a comparatively short time ago, of somewhat doubtful value. From the above, and from the fact that the duty required of a tool in one shop may be more severe than that in another, it will be seen that it cannot be accurately stated that a definite size of motor is required for a given tool. In the majority of cases, however, the horse power for small tools has been pretty well fixed. With the larger tools the variation in horse power required is much more pronounced, and at the same time, is more important on account of the size of the motors involved. This variation in horse power is often as much as 4 to 1 and sometimes even 6 to 1.

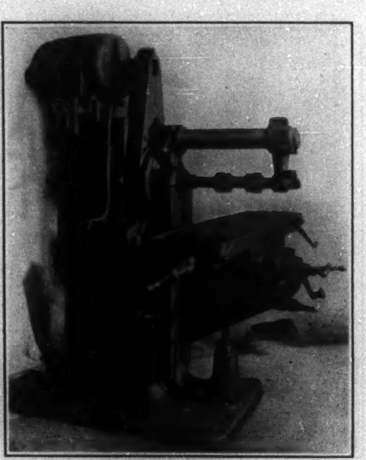


FIG. 16

Considerable difference of opinion has developed as to the advantages of individual versus group drives, and while it is generally agreed that it is advantageous to have the larger tools individually driven, the agreement by no means extends to the smaller ones. Under certain conditions there is no question as to the advantages of the individual drive for small tools, as, for instance, where small tools are necessarily placed among larger ones, or to allow convenient placing of tools in the assembling departments. The cases where it would be advantageous to have small individually-driven tools are numerous.

Little trouble is experienced in obtaining new tools already arranged for attaching motors, since many of the tool manufacturers are alive to the superiority of the motor drive and have for years built tools especially adapted for motor drives. Unfortunately, others have seen fit merely to arrange them for attaching motors, while still others leave the purchaser to attach the motor as best he can, consequently the best results are not always obtained.

FIG. 17

When the driving of old tools by individual motors is under consideration, it is important to take into account the nature of the work, the speed range, the number of similar tools to be equipped and the condition of the tool. It sometimes happens that when a tool in itself would not call for an individual drive, certain circumstances might make such a drive advisable.

As an illustration, when the majority of tools in a shop have become individually driven, there might still remain a number of scattered tools, which, unless they were driven by individual motors, would necessitate the running of a long line of shafting; or, in the event of moving into new quarters—a cement building perhaps—it is decided not to use line shafting. It is understood, of course, that when old tools are scrapped the motors can be transferred to other tools.

Some interesting methods for attaching motors to old tools are shown in the following illustrations.

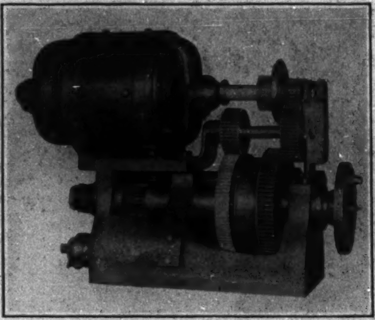


Fig. 18

Fig. 18 shows the headstock of what was originally a belted type, 24-in. lathe changed to a motor drive. This equipment makes a very durable and satisfactory drive, and calls for a standard 5-h.p., 500/1500-rev. per min., adjustable-speed motor. The shaft carrying the sliding pinions and handwheel is made large enough to receive the motor shaft, thus avoiding the use of a special armature shaft. The illustration shows clearly the motor, motor base, yoke, gears, bearing bracket and the quill which replaced the old cone. Room was left between the sliding pinion and gears in order that the pinions might be turned freely when sliding from one gear to the other.

The 30-in. lathe, shown in Fig. 19, is driven by a 5-h.p. motor, and like the lathe shown in Fig. 18, is a most satisfactory drive.

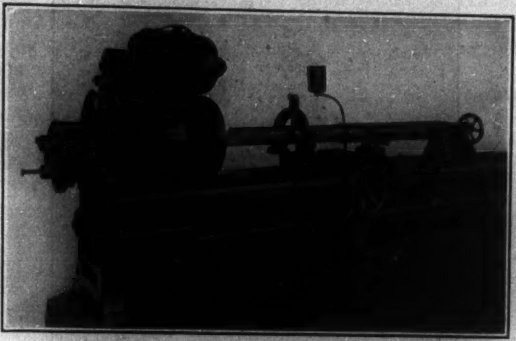


Fig. 19

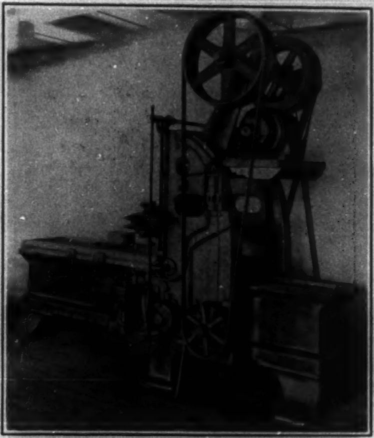


Fig. 20

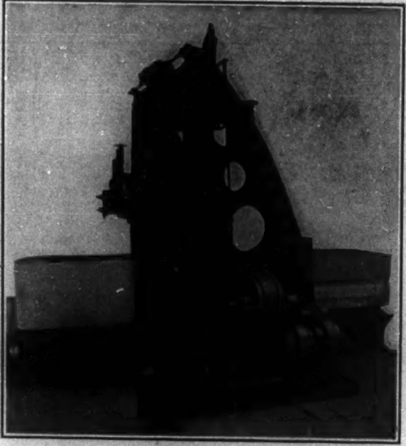


Fig. 21

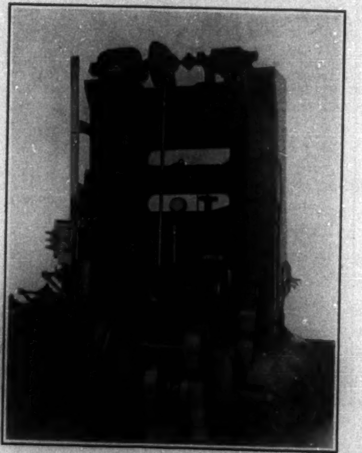


Fig. 22

It differs from the former principally in the use of a positive clutch instead of sliding pinions. These lathes, as well as the majority of lathes which are motor-driven, are operated by a handle fastened to the right side of the lathe carriage to give the operator at all times complete control over his tool.

Fig. 20 shows a 24-in. planer. This is an inexpensive way of driving planers up to 42-in. or thereabouts, and has proved highly satisfactory. It is a decided advantage to have the controller conveniently located even on planers.

Fig. 23

Fig. 21 shows an old 120-in. planer driven through pneumatic clutches. In this case there was not room for the controllers on the machine so they were placed in the most convenient position for the operator, as shown. The small controller at the rear of the large one is for operating the motor which raises and lowers the cross-rail of the planer.

Fig. 22 shows clearly the small motor for raising and lowering the cross-rail on a 72-in. planer. The main drive, which is through pneumatic clutches, is also clearly shown.

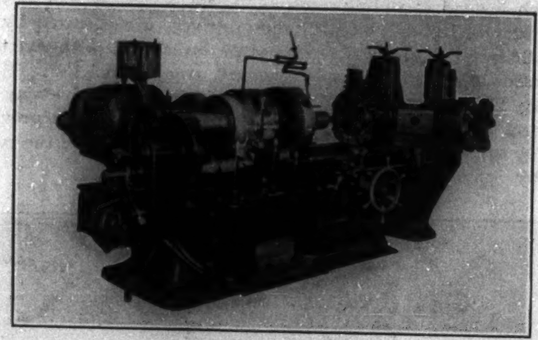


FIG. 24

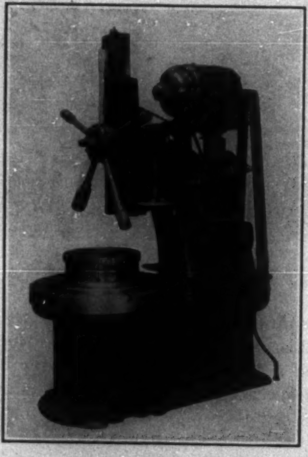


FIG. 25

Fig. 23 shows a 60-in. boring mill changed to motor drive, the cone having been replaced by gears and motor as shown.

Fig. 24 shows a turret lathe driven by a 7½-h.p., 500/1500-rev. per min., adjustable-speed motor, and a ¾-h.p., constant-speed motor.

Fig. 25 is a 36-in. chucking machine driven by a 5-h.p., 500/1500-rev. per min., adjustable-speed motor, and shows a very simple method of attaching the motor; in fact, the brackets for supporting the motor were originally made for an entirely different machine.

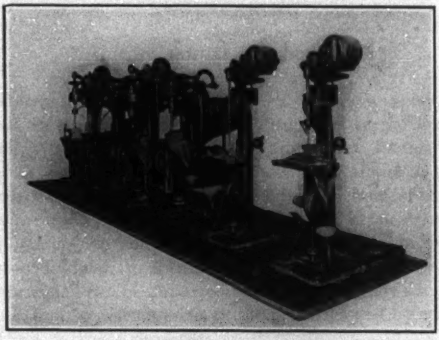


Fig. 26

Fig. 26 is a group of drills driven by adjustable-speed motors. It would be hard for one who had seen the original group to recognize this group of drills as the one originally driven by ropes, counterweights, etc.

The application of motors to tools, whether old or new, is not a difficult matter, and from the foregoing illustrations and the explanatory comments we trust that the advantages claimed for such applications have been made fairly evident.

A paper presented at the 245th meeting of the American Institute of Electrical Engineers, New York, April 15, 1910.

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EDUCATION FOR LEADERSHIP IN ELECTRICAL ENGINEERING

BY SAMUEL SHELDON

Introduction. There seems to be a prevalent opinion that engineers in general, and electrical engineers in particular, do not occupy as important positions among the leaders in this country as engineering enterprises occupy in affairs in general. An attempt is made in this paper to determine how far this opinion is warranted, to give the characteristics of electrical engineering leaders, to consider the educational advantages which they have enjoyed, to formulate those essential characteristics of leaders which can be imparted to the individual by educational processes, and to discuss some ot the problems met by educators in carrying on these processes.

The Importance of Electrical Engineering. This can be determined best from a statistical study. The following data concerning individuals and money values have their origin in various United States Census reports. Although they refer to different periods during the last decade, they are sufficiently related to warrant their use in this connection. The importance of an item is expressed by the percentage ratio which its occurrence bears to all occurrences in the same class.

The opportunities for achieving great distinction seem limited to professional service, the enumeration in the table including artists, architects, authors, scientists, clergymen, dentists, engineers, journalists, lawyers, federal, state and municipal officials, army and navy officers, physicians and teachers. However, of those having non-professional occupations there are 73,384 bankers and 792,887 merchants, a few of whom have achieved distinction in their occupations.

TABLE I. OCCUPATIONS OF PERSONS IN THE UNITED STATES, 1900

Occupations	Persons	Importance
All occupations	29,285,922	100.0
Professional service	1,264,737	4.3–100.0
Electricians	50,782	4.0
Civil engineers	20,153	1.6
Mechanical and electrical engineers	14,440	1.1
Mining engineers	2,908	0.2
Engineers and electricians	88,283	7.0
Engineers	37,501	3.0
Telegraph and telephone lineman	14,765	0.05
Telegraph and telephone operators	75,080	0.26
Machinists	283,432	0.97
Engineers and firemen (not locomotive)	224,546	0.76

TABLE II. DISTRIBUTION OF CAPITAL IN THE UNITED STATES

Distribution	Amount in dollars	Importance
Total wealth of the United States	$120,000,000,000	100.0
Electric railways (1907)	3,774,772,096	3.1
Central stations (1907)	996,613,622	0.8
Electric manufactures (1905)	174,066,026	0.1
Telephone and telegraph (1907)	1,034,909,579	0.9

The amounts set opposite to electric railways and to telephone and telegraph represent the total par value of outstanding stock and bonds and include permanent and other investments. In the case of central stations the amount represents the total cost of plants.

Assuming that one-half the group of mechanical and electrical engineers belongs to the latter class, the number of electricians and electrical engineers in the United States constitutes 4.6 per cent of those giving professional service, and 4.9 per cent of the total wealth of the country is invested in electrical industries.

The Importance of Electrical Engineers. In order to estimate the importance of engineers in the control and direction of the affairs of the country use has been made of the book "Who's Who in America," which has been employed frequently in connection with statistical studies of educational and sociological problems. It contains the biographies of several thousand persons whose achievements are widely known in some worthy line of effort. It arbitrarily includes the names of Cabinet members, Congressmen, Governors, United States and State Appellate Judges, general officers of the Army and Navy, Bishops, College and University heads, and heads of the leading national societies devoted to educational and scientific aims. In the preface of the 1906–7 edition there is a statement as to the comprehensiveness of the book, namely, that it

> " has reached a stage of such completeness in selection that very few contemporary Americans of the very highest rank of prominence will be missed from its array of notables."

All the names of Members of the American Institute of Electrical Engineers and 815 of the 4312 names of Associates, as appearing in the catalogue of members under date of August 1, 1907, have been compared with the list of names appearing in the 1906–7 edition of the above book. A similar comparison has been made with 1017 of the 2084 Members of the American Society of Civil Engineers, employing a list of members issued under date of February 1907. The number of engineers as well as the number of non-civil engineers whose names are to be found in the geographical index of the 1908–9 edition of " Who's Who in America " has also been determined. The resulting estimates of these investigations are embodied in Table III.

TABLE III. NAMES IN " WHO'S WHO "

Source of names	Number	Importance
" Who's Who " 1906–7	16,216	100.0
Members of A. I. E. E. (546)	98	0.8
Associates of A. I. E. E. (4312)	32	
Members of A. S. C. E. (2084)	259	1.6
" Who's Who," Geog. Index 1908–9	18,418	100.0
Civil Engineers in index	191	1.0
Non civil engineers in Index	367	2.0
Engineers in Index	558	3.0

Of all the names appearing in the Index, 3 per cent are of engineers—the identical percentage represented by engineers as compared with all those giving professional service in the United States, as shown in Table I.

Again of all the names appearing in the 1906–7 edition of " Who's Who " 1.6 per cent appear also in the list of members of the American Society of Civil Engineers for 1907—the identical percentage represented by civil engineers among those of professional occupation. It is probable that this list includes nearly all those holding a place in "Who's Who" because of prominence in civil engineering. The number of names, 259, is larger than that of those appearing with the special qualification "civil" in the Index, namely, 191, but there are doubtless prominent civil engineers whose names appear in the Index as "engineers" without any qualification.

It is also probable that the number of names from the Institute membership, appearing in "Who's Who," 130, includes nearly all those inserted therein because of prominence in electrical engineering. The number of non-civil engineers, 367, whose names appear in the Index, among whom are included electrical, mechanical, and mining engineers, as well as a few civil engineers, serves as a check upon this estimate. If, therefore, the electrical engineering profession be considered as embracing those who are designated as "electricians" by the United States Census enumerators, the importance of its leaders among the country's leaders, 0.8 per cent, is materially less than the importance of the profession, 4.6 per cent, and of the

TABLE IV. DEGREES HELD BY NOTABLE MEMBERS

Degrees	Number	
Without Degree		19
Bachelor's Degree		39
B. A.	16	
B.S.	16	
B.Ph.	4	
B.M.E.	1	
LL.B.	2	
Engineering Degree		45
M.E.	24	
E.E.	10	
C.E.	4	
Annapolis	6	
West Point	1	
Master's Degree		21
M.A.	13	
M.S.	6	
M.Ph.	1	
M.M.E.	1	
Doctor's Degree		35
Ph.D.	22	
Sc. D.	7	
LL.D.	4	
M.D.	2	

related capital invested, 4.9 per cent. If, on the contrary "electricians" be not included, and they cannot properly be included in the professional class, the importance of its leaders is slightly greater than the importance of the profession, but materially less than the importance of related capital. If "electricians" be considered as the educational product of trades schools, as distinguished from technical schools and colleges, the electrical engineer must still be considered, for the immediate purpose, to be not as important as his affairs.

The results thus far obtained lead to the conclusions that engineers are as notable as they are numerous and that electrical engineers are very much over-capitalized. It is possible that this may bear the interpretation that electrical engineers are overworked and that, therefore, the electrical engineering profession offers unusual opportunities for young men.

The Characteristics of Notable Electrical Engineers. The number of academic degrees and their designations, held by the 98 notable Members of the Institute, are given in Table IV.

The distribution of those degrees among the 98 Members is given in Table V.

TABLE V. DISTRIBUTION OF DEGREES

Number of Degrees	Holding Members
0	19
1	42
2	21
3	10
4	4
5	2

Of the Members without degrees 11 had the advantages of college instruction but did not graduate and 14 of the holders of one degree pursued post graduate studies without receiving a second degree. The percentage of Members holding college degrees is 80.6 and of those who have had college instruction is 90.0. The corresponding percentages for those whose names appear in "Who's Who" are 56 and 70, respectively. These Members, therefore, appear to have enjoyed unusually extended educational advantages. Especially noticeable, in the preceding tables, is the large number of bachelors', masters' and doctors' degrees, and the relatively small number of engineering degrees. This is significant as to educational influences but has undoubtedly resulted from necessity and not from intention, as will be concluded from a consideration of Table VI, which gives the age distribution of 94 notable electrical and 122 civil engineers. It should be remembered, however, that some institutions bestow a Bachelor's degree after completion of courses nearly identical with those offered by many other institutions as leading to engineering degrees.

TABLE VI. AGES OF NOTABLE ENGINEERS

Ages	Electrical	Civil
30– 34	3	0
35– 39	17	7
40– 44	22	20
45– 49	31	12
50– 54	5	13
55– 59	8	18
60– 64	5	16
65– 69	1	14
70– 74	2	11
75– 79	0	5
80– 84	0	2
85– 89	0	3
90– 94	0	0
95–100	0	1

The average age of the electrical engineers is 46.2 years, of the civil engineers, 57.5 years, and of all those whose ages are given in "Who's Who," 53.3 years. The electrical engineers are therefore too young as yet to be properly judged as to their achievements. Inasmuch as the greatest number of students are graduated from college at the age of 22.5 years, the average of the notable engineers who are the subjects of this study were graduated from college in 1883. As stated by Professor Norris, the beginnings of formal electrical engineering study in educational institutions in this country were made about 1880. This explains the smallness of the number holding the degree of electrical engineer; namely, 10 out of 140. If a subsequent and comparative study be made along the lines herein pursued in 1913, or better in 1918, the values of special educational methods may be better estimated.

Before undertaking to determine the educational attainments of the subjects of this study there must be a recognition of the fact of original nature and of its great importance in determining life's progress. Thorndike says:

"It is wasteful to attempt to create and folly to pretend to create capacities and interests which are assured or denied to an individual before he is born. The environment acts for the most part not as a creative force, but as a stimulating and selective force."

It must be postulated that persons with a record of extensive achievements are constituted of the proper clay and that notable electrical engineers have inherited the original traits essential to greatness.

Estimates of the acquired traits of these engineers have been obtained from five of their contemporaries who are considered to have good judgment, and who know many of them personally and all of them by reputation. Each of them has selected and graded ten names of those who appeal to his judgment as of greatest achievement in the electrical engineering profession. Each has also given a rough estimate as to the extent of attainment of five fundamental acquired traits an exceptional amount being marked 1 a noticeable deficiency being marked 3, and all other conditions being marked 2. The five traits were mental training, distributed and comprehensive knowledge, facility of expression, discipline of the will, and aesthetic taste. The results of these estimates concerning the twelve of highest rank are embodied in Table VII. The estimate-marks, corresponding to each trait and each person, are arranged in order one above the other, so that the mark of any judge is always in the same row relative to the top row. One judge, after selecting his ten most important individuals, seemed unable to grade them without first analyzing their traits, although he was unaware of the fact that he was to be requested subsequently to make such an analysis. This person is generally recognized as having superior judgment, and this incident is illuminating as indicating the mental processes leading up to his making of a decision. His estimates are to be found in the fifth row from the top in the table.

In the first column the individuals are represented by the letters of the alphabet. In the second column are shown the perspective or bulk estimates of the relative ranks of the individuals as given by the first four of the five judges. A numerical average of these estimates is also appended. The arrangement of individuals is not in accordance with these averages, for weight is given to the extent to which an individual appears in the lists of all the judges and to the extent of his acquirements. Thus A, B, C, and D appear in all five lists; E and G in four;

TABLE VII. ESTIMATES OF ACQUIRED TRAITS

Individual	Bulk estimate of rank		Training of the mind		Comprehensiveness of knowledge		Facility of expression		Discipline of the will		Aesthetic taste	
A	2 3 1 1	1.75	1 1 1 1 1	1.0	2 1 2 2 1	1.6	1 1 1 2 1	1.2	1 1 2 2 2	1.6	3 1 2 2 2	2.0
B	1 2 2 2	1.75	1 2 1 1 1	1.2	1 2 2 2 1	1.6	1 2 1 1 3	1.6	1 2 3 2 2	2.0	2 3 3 3 2	2.6
C	4 1 4 3	3.0	1 1 1 1 1	1.0	1 1 1 1 1	1.0	1 1 1 1 1	1.0	1 1 1 1 1	1.0	1 1 1 1 1	1.0
D	8 4 5 7	6.0	1 2 1 1 1	1.2	1 1 1 2 1	1.2	1 1 1 1 1	1.0	1 1 1 3 1	1.4	3 3 3 3 3	3.0
E	5 5 — 4	4.66	1 3 — 1 1	1.5	1 2 — 3 1	1.75	2 2 — 1 2	1.75	3 2 — 3 3	2.75	3 2 — 3 2	2.5
F	— — 3 5	4.0	— — 1 1 1	1.0	— — 1 1 1	1.0	— — 1 1 1	1.0	— — 1 1 1	1.0	— — 1 2 1	1.3
G	— 6 7 10	7.66	— 1 1 1 1	1.0	— 1 1 2 1	1.25	— 1 1 2 1	1.25	— 1 1 1 1	1.0	— 1 1 1 1	1.0
H	— 7 — 6	6.5	— 1 - 1 1	-1.0	— 1 — 3 1	1.67	— 1 — 3 1	1.67	— 1 — 1 1	1.0	— 1 — 1 1	1.0
I	3 — — —	3.0	1 — — — —	1.0	1 — — — —	1.0	1 — — — —	1.0	1 — — — —	1.0	1 — — — —	1.0
J	6 10 — —	8.0	1 2 — — —	1.5	3 2 — — —	2.5	3 2 — — —	2.5	3 2 — — —	2.5	3 2 — — —	2.5
K	— 9 8 —	8.5	— 1 1 — —	1.0	— 1 1 — —	1.0	— 1 1 — —	1.0	— 1 1 — —	1.0	— 2 1 — —	1.5
L	9 — — 8	8.5	1 — — 1 —	1.0	2 — — 2 —	2.0	2 — — 3 —	2.5	3 — — 2 —	2.5	3 — — 2 —	2.5
Group average.........				1.12		1.46		1.46		1.56		1.83

F, H and K in three; J, K and L in two, and I in but one, as will appear upon inspection of the remaining columns.

Individuals C and F hold unique positions. Of these C has a perfect score as to acquired traits, but in bulk estimate he is ranked first by one judge, second by another, and fourth by two others. A nearly perfect score is held by F, but he appears on but three of the five original lists. These apparent inconsistencies are perhaps to be explained by the facts that C has had too good taste to pursue glory or wealth while F is young and may yet have his opportunity.

The average of the estimates of the acquired traits of this group of twelve picked men shows three things: first, these men have broadly developed their faculties and have acquired to a large extent the five fundamental traits; second, they are especially characterized by their well trained minds; and third, if it be considered desirable to modify existing educational methods so as to improve upon the character of the leaders, as exemplified by the individuals of Table VII, attention should be directed toward those educational processes which result in comprehensiveness of knowledge, facility of expression, discipline of the will, and a development of an aesthetic taste.

The Acquired Traits of Leaders. Trained minds are so predominant in the Institute that a treatment of the nature of mental training and the points of differentiation between trained and untrained minds is considered unnecessary.

The extent of knowledge is nearly infinite and few have any realization of how great it is. As an illustration, in the Dewey decimal system of cataloguing books—the system in use in most of the large libraries—to each book is assigned a number which classifies it both as to its contents and as to its location upon the shelves. The first integer of its number places it in one of the following ten classes:

0. General Works.
1. Philosophy.
2. Religion.
3. Sociology.
4. Philology.
5. Natural Sciences.
6. Useful Arts.
7. Fine Arts.
8. Literature.
9. History.

Each of these classes represents a large field of human interest which can be estimated as to its extent by the number of printed books which exist as records of achievements in it. It cannot be stated truthfully that any one class is more extensive than another. Uniform distribution of books does not exist in individual libraries, but large libraries differ materially in their distributions. For instance, Brooklyn public libraries are especially strong in Sociology and Literature, but are not weak in any class.

Each of the ten classes is subdivided into ten sub-classes, which again in turn are each subdivided into ten sub-sub-classes and so on so far as may be necessary. The book receives in its number a succession of integers which successively locate it in the subdivisions of the system. In this system electrical engineering bears the number 621.3, being a subdivision under mechanical engineering, which latter is itself a subdivision under engineering, which last is a subdivision of the main class, Useful Arts. An electrical engineering book may also bear the number 537.8, as comprehending an application of electricity, which is a part of physics—one of the natural sciences. Therefore electrical engineering knowledge, as thus measured by the location of the books which record it, has an importance, with reference to the whole domain of knowledge, of two parts in 10,000 or two one-hundredths of one per cent. Of course this is not a true indication, and it would be sensational to claim that palingenesis, hermeneutics and manichaeism are fully as important as electrical engineering. But it serves to call attention to the fact that electrical engineering is a very highly specialized field for human endeavor and those who labor in it should not permit themselves to be confined to its limits.

That it is desirable for college students to gain at least a superficial knowledge of all fields of human achievement is being recognized by many educators. Harvard University has recently adopted the following rule which will go into effect with the class which is to enter next fall:

> " II. For purposes of distribution all the courses open to undergraduates shall be divided among the following four general groups. Every student shall distribute at least six of his courses among the three general groups in which his chief work does not lie, and he shall take in each group not less than one course, and not less than three in any two groups. He shall not count for purposes of distribution more than two courses which are also listed in the group in which his main work lies. The groups and branches are:

1. Language, Literature, Fine Arts, Music.
    - (*a*) Ancient Languages and Literatures.
    - (*b*) Modern Languages and Literatures.
    - (*c*) Fine Arts, Music.
2. Natural Sciences.
    - (*a*) Physics, Chemistry, Astronomy, Engineering,
    - (*b*) Biology, Physiology, Geology, Mining.
3. History, Political and Social Sciences.
    - (*a*) History.
    - (*b*) Politics, Economics, Sociology, Education, Anthropology.
4. Philosophy and Mathematics.
    - (*a*) Philosophy.
    - (*b*) Mathematics."

Leaders as a type have at least a superficial knowledge of the subject matter of all these groups and a full knowledge of that pertaining to at least one group. Formal education of engineers always comprehends some material of the second and fourth groups but is frequently deficient as to the first and third groups. Under such circumstances the graduate attains a knowledge of things and his thinking self, whereas he is left ignorant concerning the methods of thought and of action of man and men. Such ignorance is fatal to leadership, for the very word implies a man to lead and men to follow.

Facility of expression, spoken, written, or wrought, is essential as a vehicle for the conveyance intact of the definite concept of the brain of the man to the minds of other men. Other things being equal, the engineer who can speak effectively, as well as write, is the engineer who will exert the widest influence. Skill in the oral presentation of a plan, in the defence of a position, in the advocacy of a reform, or even in the making of a graceful and apposite response to a toast, has largely contributed to many a man's success. It is especially desirable for those who hope to occupy positions of executive responsibility.

To say that a disciplined will is essential to leadership is to utter a commonplace. In these times of intense life, when fatigue prevails, when haste kills perfection and thought robs sleep, it is indeed a luxury to remain a leader. Will's control of desire must be absolute.

That elusive trait, aesthetic taste, is essential for admission to the aristocracy of culture. It must ever remain indefinite and will not submit to standardization. While some of its elements may be present at birth others may undoubtedly be acquired, with a resultant modification of the complex.

Doctor Johnson distinguished between natural and achieved taste. He said that if he had no duties and no reference to futurity, of all things he would like to drive briskly in a post-chaise with a pretty woman at his side. This was his natural taste. At the same time he said to Boswell:

> "Do not, Sir, accustom yourself to trust to *impressions*. By trusting to impressions a man may gradually come to yield to them, and at length be subject to them, so as not to be a free agent, or what is the same thing in effect, to suppose that he is not a free agent."

That is, our natural likings and dislikings are no safe guides; they must be controlled by education.

It seems evident that a man cannot become a leader of men if he be proscribed from intercourse with those who are wisest and most influential.

The Educating of Engineering Leaders. If it be assumed that engineering students, to become leaders, must acquire by education the fundamental traits which have been discussed, present methods pursued in their education could be improved upon.

Consider, first, existing institutions which have the usual requirements for admission and which bestow an engineering degree after four years of work. Their courses and methods could be so modified as to better the chances for leadership of all their students. The modifications should be three-fold and as follows: (1) a new system of selection of entering students should be adopted, (2) new subjects and methods should be introduced, and (3) time must be found for new subjects. The details of these modifications lie without the scope of this paper, and the wisdom of attempting them is questionable, for existing institutions, which are supported by the state, should be inclusive rather than exclusive, and those which depend upon distributed philanthropy must ever present the plea of extended usefulness.

A more discriminative system of selection at entrance would undoubtedly decrease the number of students and increase their average age. Of course a better resulting quality of product would be expected after four years. The great advantage to be obtained, however, by this discrimination, is the elimination of students of harmful influence, whose characters or circumstances militate against earnestness in endeavor and discipline of desire.

One subject of tremendous educational importance is recommended for consideration, namely, an extended study of literature as an art by the appreciative method. Art orders experience by the imagination, employs particularizations presenting truth concretely, and appeals to the emotions, to the will, and to the taste as well as to the intellect. Literature is preeminent over the other arts—for its range of suggestion is the widest, it offers the most complete and definite intellectual content, and it represents life most fully. Its study develops the imagination and as Woodberry says:

> " So far as we realize the world at all beyond the limit of our private experience of it, we do so by the power of the imagination acting on the lines of reason. * * *. The scientist lights his way with it; the statesman forecasts reform by it, building in thought the state which he afterward realizes in fact; the entire future lives to us—and it is the most important part of life—only by its incantation."

It is significant that, of the 35 volumes which constitute the five-foot-shelf library of Dr. Eliot and which are considered by him to contain the elements of a liberal education, 22 have been classed by an expert cataloguer as " literature ".

The education of leaders and of all engineers does not cease until their retirement and the problem in hand relates to what may be termed their formal education. The general type of engineering leader has enjoyed more formal education than would be represented by the ordinary four-year course. A modification of this course so as to make it an equivalent would probably result in a corresponding rise in the average age of graduation. Those who recognize the long time required make different recommendations as to how it should be occupied, as an arts course followed by an engineering course, an engineering course followed by an advanced arts course, or a simultaneous pursuit of an arts and an engineering course. The last has some points in its favor, for maturity is an important factor in the successful pursuit of some arts as well as of some engineering subjects. But all these plans are faulty, in so far as they contemplate the inclusion of arts courses as they are at present taught in the ordinary college. There is a total lack of adjustment between the colleges and American life, as evidenced by a series of papers on this subject presented by prominent educators at the last Baltimore meeting of the American Association for the Advancement of Science. Especially evident is the lack of coördination between the arts courses and the engineering profession. Until the demands of law, of medicine and of trade are met by adequately modified curricula and methods of teaching a marked improvement cannot be expected in a plan of engineering education which includes this instruction.

But is it not folly to attempt to educate all when the presence of the many who are sure to fail impedes at every step the progress of those who are destined to succeed? Institutional rivalry and individual ambition may say nay, that it is the way of democracy. But, if West Point, with its 500 cadets, can so adequately supply the leaders for 80,000 armed men, could not an engineering school of similar proportions supply the leaders of engineers? With the assurance of continued opportunities for promotion, would not choice residues follow each process of elimination? What might not a professor accomplish with such material? With practical skill, acquired in the post graduate laboratory of organized experience, what difficulty could be encountered in the construction of a Panama Canal? Is not the performance of such a task of greater value to civilization than that relic of barbarism—a victory at arms? The entire feasibility of such an institution makes one long to see it building. If Federal support be lacking, why not that of those whose wealth increases each day as the sweat pours from the face of the engineer?

DISCUSSION ON "EDUCATION FOR LEADERSHIP IN ELECTRICAL ENGINEERING", NEW YORK, APRIL 15, 1910.

Charles S. Howe: I shall not attempt to discuss all of the interesting questions which have been raised by Professor Sheldon, but only one or two points which have struck me most forcibly. Professor Sheldon says that the electrical engineers who have attained an eminence in their profession do not seem to have engineering degrees, at least very few of them have the degree of E.E. Now, we have found in discussing the reports which have come from the various engineering colleges, that very many of the engineering colleges do not give the degree of E.E. One or two of the oldest and most noted of the technical schools in the country do not grant the degree of Engineer at all, and I think that this may account in part, at least, for the fact that so few of these eminent engineers have the degree of E.E.

In discussing the question of leadership and the preparation for leadership, I am led to say a word or two in regard to the education which we are trying to give in the technical schools, which I believe is along the proper lines, whether for the training of the ordinary engineer or for the training of the engineer for leadership. Among other things, we are trying in the first place, to give the students a certain amount of knowledge. I sometimes think that perhaps we lay too much stress upon that. In the past that has been our principal object, but nevertheless, we must give the student a certain amount of knowledge— a great number of facts, and of course, he forgets most of this before he graduates. But far more important than the giving of facts by teaching a few definite things, is the ability in the student to know where to find the things he wants at any time of his career. That is, the ability to search. If he has been properly taught to search he will have received something far more beneficial to him than the few facts which he has been able to digest and carry away with him.

I believe that in our technical schools we have not paid enough attention to this branch of education, that we ought to teach our students to use dictionaries, and encyclopedias, and books of reference, libraries in general, the catalogs of the great manufacturing establishments, the magazines, the special reports of societies, etc., until, when a student is confronted with any problem, he will practically know just where to go to find the proper information upon that subject.

The other thing which we should try to teach him is to think, to reason for himself. That is the hardest task which we have. I believe, however, that it would be possible to lay out a systematic course of instruction in teaching students to think for themselves.

Most men are not leaders, as Professor Sheldon has said, they are men who follow, they follow the men before them, and this process of thinking is, as a rule, at the present time learned by men themselves, without very much instruction on the subject. If we can only develop methods by which students will understand the laws of learning to think, to think along engineering lines, we shall greatly increase the number of leaders, and I believe the leaders themselves will be still greater leaders.

Professor Sheldon has emphasized the importance of broad knowledge, of facility of expression, etc., and I believe that he has rightly done so. The technical institutions are fast coming to the point where they believe that the instruction in engineering colleges should be broader than it has been in the past. Perhaps it might well be asked why we do not now insist that every student coming to a technical school shall first be a college graduate. The reason, of course, has been that the technical schools have utterly been unable to graduate men enough to fill the places open for them. If all the technical schools required a college degree for admission, we would not be able to graduate more than one-quarter as many students in technical schools as we now do, and there would be a smaller proportion of men ready to take the positions which are open to the technical graduate. That is the reason why, in the past, we have not insisted upon the broader training.

I fully agree with Professor Sheldon also that men should be taught facility of expression. The subject of English composition and rhetoric especially has been greatly neglected in most of our technical schools, until within a very few years. Now we are beginning to devote more time to this subject, because we are finding out that the technical graduates we have been sending out without any ability to write, without any facility of expression, do not succeed as well as the men who can express their thoughts well upon paper and present engineering subjects to Boards of Directors or to organizations like this.

Professor Sheldon also made some suggestions in regard to improvements which might be made in the technical schools. He speaks of new methods of admission. I do not know whether it is possible to find any way of admission by which we shall be able to find a set of men of greater ability, more energy, who will take higher rank in their studies, and who will make better engineers after they get out into the world. I doubt if we can do it by any system of entrance examinations. We can do it, however, by weeding out the students while they are in the college. Of course, the technical school does that now to a considerable extent. I think, possibly, the process at times might be carried further.

Dr. Sheldon has said that new subjects should be introduced. I heartily agree with him. There are many things we ought to teach in the technical schools which we do not teach now. It is also suggested that new methods should be employed, and again I think he is entirely right. Whether it is going to be possible to teach new subjects and use new methods in a four years' course, I am very much in doubt. I rather think that the technical schools are coming to the conclusion that in the future we must have a five years' course instead of a four years' course. Whether we shall be able to train any more men for leadership, I do not know. Leadership depends upon many qualities. Now, we can only take the product which comes to us, and try to improve it. We cannot make native ability, and some of the qualifications for leadership are the natural qualifications of the man. These we may improve, but we cannot create them.

Another thing which is necessary for leadership is the ability to get along with and to handle men. That is something that it is exceedingly difficult for us to teach in the technical school. It is the man who can work with other men, get along with them, and handle them, who generally achieves the greatest success.

Abraham Flexner: It seems to me that in this country we have been rather apt to concentrate our educational processes on instrumental proficiency, on the making of men who could do particular things efficiently and well—good surgeons, good doctors, good lawyers, in the narrow and professional sense in which those terms are used.

The problem which Mr. Sheldon raises, namely as to how cultural and vocational standpoints can be combined in any one educational discipline, is fundamently a logical before it is an educational problem.

We are dealing here with two apparently exclusive concepts, culture and vocation. We ordinarily apply the term " Culture " to experience in so far as it is expansive, sympathetic, enlarging, releasing; we distinguish from culture " vocation ", as practical, immediate, concentrative, limiting. To the engineer, culture would seem to be art, history, economics; but to the artist, the activities and implications of engineering would have to represent the enlarging, releasing, that is cultural aspects of experience.

The attempt to conceive the cultural and the practical as different in kind would, however, break down of its own weight; for obviously, any one object or interest can be either the one or the other by turns.

If, now, one particular content may, according to point of view, serve in both capacities, being simultaneously culture to one man and vocation to another, it is obvious that the distinction is not really fixed and fundamental. The actual relation, instead of being one of permanent opposition or contradistinction, is, I think, rather to be likened to the relation between a map and any town or state upon it. On a map of the United States the state of Ohio is, the moment one's attention is concentrated upon it, seen as against all the rest of the map. None the less the state is all the time part of the map, from which it is at the moment, and from a particular point of view, abstracted. We can, I think, conceive the logical relation between culture and vocation in some such form.

Within this inclusive mass, certain typical forms are differentiated for practical purposes; and any one of them, as seen isolated from, and against the background of, all the others, becomes an occupation, a vocation, emphasis upon which proceeds from practical necessity. Any single aspect, when emphasized, concentrated, separated out, from the mass, becomes then the vocation of the man who is thus engaged. Everything else, representing experience that is beyond him, that he must reach out for and go out of himself to get, is, as we say, culture.

The apparent change in the stuff itself is thus the inevitable consequence of the changed angle from which it is regarded. The vocational view is near and detailed because the eye is fixed, the hand ready to act; the cultural view is vaguer, less responsible, more wayward, because it tends to leave the immediate in order to follow out suggestions and clues. It is indeed a rare individual that takes easily by turns both attitudes towards a single object—as, for example, Metchnikoff can and Goethe could do.

If then, the distinction between culture and vocation is thus shifting, conventional, a matter of convenience, a temporary point of view, it is clear that there is a certain untruthfulness and inadequacy involved whenever the effort is made to isolate vocation from the cultural plexus, to treat it wholly within itself. Provisionally such isolation is, of course, warranted in so far as it serves a purpose. But relations are falsified if the lines are held tight. The inadequacy of a specific and narrow treatment of engineering education, such as Mr. Sheldon has pointed out, is due, I think, to this unnatural separation of the practical ingredients of engineering as a vocation from the social background and interrelations which really constitute the opportunity and content of engineering as a profession.

It is no more possible to realize in its fulness the meaning of engineering or of medicine (when they are taken alone) than it is possible permanently to treat the state of Ohio as an entity. Within any one geographical division there are indeed certain relations to be established and certain facts to be learned. But our knowledge of it is dead unless these threads are followed out beyond state lines into the rest of the map.

If, then, this logical relationship that I have pointed out is sound, it follows that vocational or professional training must have a background, the whole background of our social life, just as the activities and interests of engineering must themselves be part of the background for men whose vocations lie in other parts of the field.

The word cultural cannot then be restricted to any particular set of interests and activities. It is nothing but an historic accident that the untechnical treatment of literary and artistic subjects has come to be specifically known as culture.

The details of an educational scheme which shall seek to put into effect the relationship that has been pointed out can hardly be discussed in the few moments at my disposal. We have learned well enough how to educate for the vocational life; but not as yet how to achieve the vocational with due deference to the cultural, as the Germans have done; we have yet to solve that problem. The medical schools are just now experimenting with what they call the combined course—the effort, that is, to combine the cultural and the vocational treatment of certain fundamental medical sciences.

The technical training of the engineer, like the technical training of the doctor, is focused on details; it does not lift its eye to follow out into the tangle of life the lines of suggestion that would enrich and diversify and enlarge. It stops at the state line, to recur to the metaphor of the map. And all the time this unnatural isolation defeats itself—for the engineer, like the physician, is one of the builders of the future. The narrowly technical education makes him just instrumentally proficient; only if his training extends out into the cultural tangle, will he get a voice in determining the line that social evolution shall take, only then will he be a creator of the future and not merely a tool of the present.

I wonder if it may not turn out—I speak very hesitatingly here—that the engineering school will have to define its purpose anew, revising its procedure in conformity therewith. Four years do not suffice to produce a highly specialized engineer, with cultural outlook besides; to train a boy in both instrumental and cultural mastery of the art. Perhaps the lines of the technical school may have to be laid down more broadly, on the assumption that a subsequent apprenticeship may shape the young graduate to his definite practical use. Time and interest might thus be gained within or prior to the engineering course for the cultural as well as the technical treatment of the content of its curriculum.

Doubtless such a treatment sounds very leisurely just when we are finding time too short. I believe that economical use of the years available for schooling will make possible interesting and perhaps successful experiments in this direction. At any rate let us not be afraid to experiment. Outside the elementary school we are not as yet, unfortunately, given to educational experimentation. I cannot believe that there is really anything to be feared in conceding to secondary school or college teachers a much freer field of experimentation than they have as yet been allowed. As a matter of fact, the great problem in education as in society, is not how to prevent, but how to secure innovation.

In this new modern world, which the engineer has done so much to reconstitute, we creatures of habit, continue in a futile and feeble way to do the things that have been doing for centuries past. It will take a good deal of philosophic and logical dynamite to blow the thing to pieces and clear the way for a fresh, adequate, and modern construction.

J. W. Lieb, Jr.: We are living in a practical age, a period of intense industrial activity and large accomplishments—ours is the age of coöperation and efficiency. It is not enough that a given task be accomplished, or a vast public work completed, the world asks also, has it been done efficiently, with a reasonable economy of time and money, and with a proper adaptation of the means to the end.

While this close scrutiny is given to the relation between expenditure of effort and result achieved, between input and output, between cause and effect in the material accomplishments of our times, a scrutiny not less searching and thorough is being directed to our educational methods and their highest product—the college graduate.

One of the important questions occupying the public mind at present, and upon which the searchlight of inquiry is being directed, is this:

Is the college graduate of to-day, the finished product of our universities, our colleges, and our technical schools, occupying a position in professional activities, in the industrial world, and as a citizen, which justifies the expenditure of time, money, and educational effort sacrificed in his preparation?

Is the college graduate successfully fulfilling a distinct mission in our social system not only in furthering industrial developments, not only as a leader in thought and an exponent of culture in its highest sense, but also as an effective force making for righteousness in the community, and is he making his service and sympathies felt in the uplift and progress of humanity?

Is his success in life—measured also by purely commercial standards—such as to demonstrate without question that the time and expense necessary to produce him, is a wise investment?

I think Professor Sheldon has afforded several clues to the consideration of some of these questions. He has referred in his paper to the specialization in the field of electrical engineering. This hardly needs emphasis, as we know that in our institution, the American Institute of Electrical Engineers, we are beginning already to sub-specialize within the domain of electrical engineering, and we find that this subject of itself is becoming already too broad for one man to become expert in all of its ramifications. This has also taken place in the past history of the broader field of engineering, and now the technical schools in mechanical engineering find it most difficult to fairly cover the field with the tremendous expansion which electrical engineering has brought about, and they are face to face with the proposition of subdividing their courses into the several constituent fields.

Dr. Sheldon has referred to the importance of facility of expression, both oral and written. This is a subject which appeals to me very strongly, because as a matter of experience, I have found that it is one direction in which the product of our technical schools is most apt to be deficient. The product of the technical school has had strongly instilled into him the power of analysis, the method of approach, the weighing up of the pros and cons of a problem, but it is my opinion that he has not been sufficiently well grounded in the power of expressing and of presenting his conclusions. This is a most important element, a most important faculty, which the successful engineer should possess if he wishes to present his findings and have them adopted; the power to clearly and strongly present his views, to be able to defend them with good judgment and force, so as to impress the people who are to place their money upon his judgment. In this particular direction it appears to me that our technical schools might well devote a larger share of attention.

It has seemed the purpose of the discussion to take up the suggestions which Dr. Sheldon has made as to the modifications in the present methods of technical instruction. As one grows older, one feels the lack of the broader culture to which repeated reference has been made, which it has not been possible for the technical schools to give. This is a serious proposition, as we are already face to face with the evident necessity of expanding the course from four to five years. This expansion is of pressing importance, from the standpoint, one might say, of vocational requirements, and where, usually, the time for a wider acquaintance with the humanities is not afforded. This is a serious question which the engineer is facing. It is almost impossible for the engineer to make up for lost time after graduation. The necessity of following the tremendously rapid developments in all of the fields of engineering makes self-culture a matter of extreme difficulty; and therefore, the most that the purely technical school can hope to accomplish is to instill into the minds of the students a love for purely cultural studies, for literature, and art, in all their various manifestations, in the expectation that they may be followed during more mature opportunities that come in after professional life.

We all know that the responsibilities resting upon the engineer are ever increasing. Many subjects, such as old-age pensions, systems of compensation for labor, prison labor, child labor, and subjects of this character, are left in the hands of lawyers or professional politicians. Now, this should not be the case. The professional engineer who has come in contact with these subjects in their various manifestations should take a more active part in developing the public mind and directing the activities of the state and the nation in the direction of meeting these living questions. In order to do this it is necessary for the engineer to have something more than a merely vocational training, it is necessary for him to have a wide basis of culture, wide human sympathies, and a wide knowledge in many fields; and it is to be hoped that our technical schools will rise to the opportunity of conferring upon their students a more thorough recognition of the value, even to the vocational man, of a broad basis of culture and entertainment.

A. E. Kennelly: Some of the statistics presented by Dr. Sheldon, while they seem strange at first sight, may perhaps be explained without great difficulty, as he has himself suggested. For example, the fact that there are comparatively few electrical engineers with the degree of M.A. is a fault that time will rectify; because there has not been opportunity in the past to obtain many electrical engineers among the men who have received that degree. Again, the fact that we have no notable electrical engineers over seventy-four years of age, ought not to be interpreted on the understanding that the good die young, because the profession is still too juvenile.

In regard to the vexed question as to what subjects are cultural and what subjects are vocational, I would venture the proposition that all subjects are either vocational or cultural merely according to the way in which they are taken and given, and that there is no other criterion. In fact, I would go so far as to say that in a certain sense all subjects are equally worthy and equally grand. There is no subject which, of and in itself is more worthy or more deserving of study than any other subject, if treated in a broad sense. It is only when considered with reference to some particular vocation, or some particular duty that certain studies become of preeminent importance. The selection of specific technical subjects of study is of absolute necessity, in order to economize time; because the training years are limited, and we cannot indefinitely stay in school.

In regard to the requirements or qualifications for leadership, I think we must all agree with Dr. Sheldon in the general propositions that he offers, but I think there is one item that deserves some emphasis; namely that the qualifications which are competent to train men to lead are also qualifications that train men to follow; that men, before leading, must be able to follow, and that the requirements of the man who shall follow are discipline, and faithfulness, and earnestness in whatever he undertakes.

It seems to me that the qualities for training in following, depend largely upon the cultivation of ideals. Ideals cannot be created any more than learning can be created, but ideals can be fostered.

I believe that the elevation of ideals is of the greatest importance, so that anything we do, whether we sweep a floor or put up a station, may be done with the best of our ability, and with whole soul. By that criterion alone is our work to be judged.

William McClellan: I think it would be interesting if Dr. Sheldon, in connection with Table 7, would arrange to weight the various qualities, instead of considering them all of equal value, so that when we come to the general average, we should have some way of discovering whether the judge would claim 1.83 or 1.12 as a direct comparison. In other words, would he consider "training the mind", "comprehensiveness of knowledge", "facility of expression", "discipline of the will", and "aesthetic taste" as all of more or less equal value.

We all look at questions of this sort from different points of view, and as I think of the men whom I should consider leaders in electrical engineering, I find that their leadership is not on account of their wide knowledge of electrical engineering but is due to their having the same qualities that make certain lawyers, clergymen, or medical men leaders. That is to say, it is these characteristics or attributes of the man, himself, which give him leadership and that these characteristics or attributes are general.

Now, it may be stated quite positively that a large accumulation of detail information does not make a man a success. Success comes from reasoning along original lines,and such reasoning is possible only if the man has a thorough understanding of fundamental underlying principles.

History has shown that a physicist or a chemist with a thorough understanding of the composition or properties of matter has been able to do engineering work of the highest order when called upon, although his training in details of engineering has been very scanty.

The possession of this general fundamental information by a man on leaving college is all the more important when it is remembered that, for the most part, he is hunting for a job and is willing to take it in any branch of engineering, whether in the particular one for which he prepared or not.

I believe that there is sufficient evidence now of a change in our educational courses to show an effort to produce men trained as engineers rather than as certain kinds of engineers. Unity is being introduced gradually; and, perhaps, some day, we shall have a broad profession of engineering, like, at present the professions of law and medicine.

Personally, I should be very glad to see the colleges of the country give up all consideration, in the undergraduate courses, of special engineering degrees; and give to all their students the same course, graduating them with the degree of Bachelor of Science.

In the arrangement of our college courses, we could learn a great deal from a consideration of what is done in medicine and in law where the undergraduates take practically the same studies barring, perhaps, a few electives in the senior year, and specialize when they get out into practical work.

President Stillwell: I want to call attention to two things that have been emphasized particularly. In the first place, I do not agree with Mr. Lieb entirely with regard to what he said about the difficulties of self-culture after graduation. I believe that the man who stops his education upon graduation, and exclusively specializes, makes a great mistake. There are any amount of opportunities for a man to continue his education in a manner that is broadening and effective. The other suggestion is this; that education in almost any line that teaches logic and a sense of proportion is engineering education. In constructive engineering the most valuable faculty, in my judgment, is that which may be designated as the sense of proportion, what the painters would call perspective.

In one large engineering undertaking some years ago I had occasion to have the number of contracts determined which entered into the equipment; which had nothing to do with civil engineering, nothing to do with the digging of holes in the ground, but simply with equipment, mechanical and electrical. These contracts were not divided, they represented links in a chain. There were one hundred and seventy of them. Now, I think it is not often realized that there are so many factors entering into a large modern engineering construction in the electrical and mechanical field. No mathematician can possibly produce an equation representing the values of the factors entering into that aggregated plant. The mental characteristic, which is comparatively rare, and which after all is the most valuable, is something which may come partly from education, but I believe it is largely innate, that is, proportion and judgment, to determine relative values, and to aggregate the factors which enter into one of these complex matters in a manner that will produce an operative, well balanced and economical result.

Wm. J. Berry: The discussion of this paper has been very interesting, and all the speakers seem to be in substantial agreement with the writer. It is surely most significant that men who have attained eminence in the practice of their profession have joined with educators in pleading for a broader training for the engineer. It seems to me, however, that we are in grave danger of losing sight of an important factor in the problem of engineering education—the student himself. There is a certain limit beyond which not even the best student can work efficiently, and in planning our curricula, care must be taken not to exceed the average limit of the students who remain after all the elimination tests, to which reference has been made, have been applied. Some of the " haste which kills perfection," of which Professor Sheldon speaks, has, undoubtedly found its way into our technical schools through a desire to do more than can be accomplished with thoroughness in the allotted time.

The college of the humanities, aiming to give cultural training, applies to the subjects studied the extensive and appreciative method; the technical school, the purpose of which is vocational instruction, employs the intensive and critical method, yet the latter institution usually requires a greater number of courses than does the former. Harvard College demands for the bachelor's degree a minimum of seventeen and one-half courses (or the equivalent in half courses) of which not more than six may be taken in any one year. recently there came to my notice the case of a student in an engineering school of established reputation, one of the best two men in his class, who, at the end of the first semester of his senior year had to his credit the equivalent of sixty-one half courses, representing a total about double that of a college senior, and an annual average of seventeen half courses as compared with the latter's maximum of twelve. The college man spends from fifteen to twenty hours a week in attendance on lectures, the technical student devotes from thirty to forty to required work in the lecture hall and in the laboratory.

We are all agreed that the ideal training for the engineering leader must consist partly of vocational and partly of cultural subjects in the sense in which those terms were defined by Dr. Flexner, but even with the five years course suggested by Professor Sheldon, not many new subjects can be added to the existing curricula, unless it be possible at the same time, to eliminate some of those already present, or better methods of instruction can be found than any now employed.

A. S. Langsdorf: It seems to be the general opinion of contributors to discussions on engineering education that the average product of the traditional four-year course is, if not actually mediocre, at least so little beyond that stage as to be damned with faint praise. Most criticisms of the usual curriculum are so vague in their constructive tendencies as to be valueless, while many offer remedies impracticable because of the limited time available. But to whatever extent the strictures are justified by the facts, it cannot be questioned that Dr. Sheldon has gone to the root of things by pointing out the necessity of adopting a new system of selecting entering students; for that, to my mind, is the crux of the whole problem. It may well be doubted whether refinements of the course of study are of any value to a student who lacks some generations of cerebral development, no matter whether that lack be due to heredity or to early environment.

Any one who has had to do with the administration of technical schools knows very well that the hardest work falls upon those whose duty it is to eradicate from the freshmen mind the "kindergarten idea" of education. Our preparatory schools are so strenuously engaged in maintaining the pupils' interest that there has been a distinct loss in the disciplinary features that make for real efficiency; the interest of the student is an important element, but it is not the paramount issue.

The institution which aims to develop leaders as its principal output, and not as a by-product, must deliberately put aside the temptation to brag about the size of its student body, and must recognize the fact that there is such a thing as an aristocracy of intellect. While any man is the better for a schooling, it is given to few to be educated. It has been said that the American standard in higher education is a rather high average and a corresponding low maximum; what is wanted is an educational "load curve" with more "peaks", or at any rate, higher ones.

Signs are not wanting that technical schools are alive to the demands being made upon them; witness the developments of recent years in the way of lifting engineering education to a really professional basis by the introduction of more or less complete graduate courses. It is a practical certainty that engineering education is going through the same evolutionary process that has characterized the development of medical education, and for identical reasons.

Samuel Sheldon: In reference to the discussion of Mr. Howe, with regard to my recommendation that a new system of selection of entering students should be adopted, I think it is well recognized that nearly one-third of entering freshmen should never have come to the technical school. What they lack is not that which the school or any one else can give them, but is natural ability. Examinations, conducted along standard methods and lines, cannot determine much else than the candidates' acquired abilities. There should be, it seems to me, for proper justice to those who are expecting to become educated, an examination that will determine whether or not the proper natural traits are present.

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EMERGENCY GENERATING STATIONS FOR SERVICE IN CONNECTION WITH HYDROELECTRIC TRANSMISSION PLANTS UNDER PACIFIC COAST CONDITIONS

BY A. M. HUNT

No matter what care and skill are exercised in designing and constructing a hydroelectric plant, with accompanying high-tension transmission lines, absolute continuity of service is a thing which cannot be assured. This is more particularly true of our western plants as compared with those of the eastern section of the country, and is especially true in California. Practically all of our important hydroelectric plants are located on streams which find their way down the western slope of the Sierra Nevada range of mountains through deep canyons. The sides of the canyons are usually very steep, and furnish very poor foothold for ditch construction. The cost of driving tunnels is usually prohibitive, and in the majority of cases, box flumes, built of lumber, are used to carry the water.

Our winter season is one of rains and heavy precipitation, and it is not infrequent that flumes go out, due to water-soaked foundations, slight leaks undermining footings, breaks caused by falling rocks, or other causes. This means an interruption of power service. Interruptions may and do come from line troubles due to many causes.

Interruptions of service were more than occasional in the earlier days of transmission work on the coast, and even to-day with the better construction and design, and greater care and watchfulness in operation, they occur often enough to be matters for serious consideration.

The best means for avoiding the serious results from interruptions of service, is to reduce the period of time during which power is off the line. Any interruption of service is serious, but if a prospective power purchaser could be assured that his interruptions would be a minimum, and that when they did occur, they would be of very short duration, he would not be so apt to refuse to purchase power from the hydroelectric company on the score that the supply was not dependable. Such shortening of duration of interruption can best be accomplished by having at the receiving and distributing point an emergency generating station, maintained at all times in such a state of preparedness that it can be started and put on the line in the shortest possible time.

Under the conditions existing in California, it may become necessary to operate such a stand-by plant continuously for considerable periods, due to seasons of low water, and it is, therefore desirable that its economy should be good. In fact, I believe I may safely state that no stand-by plant has been installed on the coast which has not become an important operating factor of the system with which it is connected.

I propose to discuss the type of stations for this service, making comparison between a station having generators driven by gas engines, and one in which steam-driven turbo-generators are used. I shall try to establish the thesis *that the turbine station can be so designed as to be built at much less cost than the gas-engine station; that it can be kept in a state of preparedness where it can be put into service on the line as promptly as the gas engine station; that its stand-by charges will be less than for the gas-engine station; and that its economy, when called on for continuous operation, will be at least as good as that of the gas engine station.*

Premises Assumed. The station shall have a capacity for continuous operation of 25,000 kw. at 85 per cent power factor.

Crude petroleum will be the fuel used both for generating steam and for gas making.

The station to be located at a point where spur-track facilities are available, and where ample water supply can be had.

In making comparison of economies with station in continuous operation, it is assumed that the load factor will be 50 per cent.

General Outline of Gas Engine Station

The station will contain 12 units, each having a continuous load capacity of 2085 kw. at 85 per cent power-factor. The size of unit is small for a station having such a large capacity, but it is extremely doubtful if any of the engine builders will agree to build and guarantee larger engines, especially for use with gas made from oil. The experience with the large gas engines in the Martin station of the Pacific Gas and Electric Company indicates that the safe limit was passed there.

The following quotations from recent letters received from one of the large gas-engine builders is also confirmatory:

> From reports made by various members of our engineering department, who have noted the large continental engines in operation, we gather that while some very large cylinders are still operating in the single-acting type, the European, and particularly the German companies, who have built larger than 42 inch or 44 inch diameter, using cast iron as the material, have been compelled to replace practically all of their cylinders, leads us to believe that they should not be attempted at all in cast iron, and if steel is used with cast-iron bush, the cost per brake h.p. will be much larger than a smaller sized unit, without any gain in efficiency or lessening of operating expense.
>
> If economy is the controlling factor, it would seem to us that a size such as our 37½ in. x 48 in. (3100 brake h.p.), which can be made safely, with cast-iron cylinders would be a better proposition than a larger engine with longer stroke and larger diameter of cylinders which it would be necessary, or desirable, at least, to make of cast steel. We can readily understand how large power houses want turbine units of very large capacity of 10,000 kw. or more, as the economy of the turbine unit increases perceptibly as the sizes grow larger, and these very large units can show economies which are difficult to reach with the smaller sizes, but with the gas engines, if there is any difference at all, the reverse is the more likely to be true, as cylinders of moderate size can be effectively cooled and used with water of ordinary temperatures, while with the very large cylinders, in order to keep certain spots from getting hot enough to ignite the gas, other parts of the cylinders have to be kept unnecessarily cold. The desirability of good parallel operation also tends to cause a choice of smaller cylinder diameters, as with very large engines the slow speed and great number of poles cause the generator builder's requirements for operation to be very close indeed, and the weight of the flywheels becomes prohibitive, both from the point of first cost and from the ability of the bearings to stand the load without heating.

The gas required per 24 hours will be 7,500,000 cubic feet, based on 650 B.t.u. per cubic foot, 50 per cent load factor, and assuming that by reason of the relatively small size of units, the engines will always be operated at approximately full load.

The gas-generating plant will consist of three oil gas sets, each capable of producing 2,500,000 feet of gas per day, with necessary condensers, scrubbers, and purifiers, and a holder capacity of 2,250,000 cu. ft. to equalize the daily load. It is assumed that the units will have twin tandem engines, and the over-all size of foundation for one unit will be 70 ft. by 30 ft. Allowing for passages, the size of electric generating station will be 76 ft. by 400 ft. if engines are placed in one continuous line, or 152 ft. by 200 ft. if placed in two parallel lines. The station will have the usual compressed-air starting equipment.

General Outline of Turbo-generator Station

This station will be assumed to contain two turbine units, each having a continuous capacity of 12,500 kw. at 85 per cent power-factor. Each unit will have its condensing equipment, and the boiler plant will contain water-tube boilers in units of the largest size available. The boiler settings to be built so as to lose as little heat as possible by radiation from exposed surfaces. All boilers to have tight fitting dampers, which may all be opened from a central point. The oil and steam supply for burners to be controlled from the same central point, and so arranged that burners may be operated from such point. It is also figured that igniters will be fitted in the furnaces which can be operated from the central point, so that fires can be started under all boilers simultaneously.

The boiler capacity in the station is assumed to be such, that maximum load can be carried by forcing boilers 33⅓ per cent beyond builder's rating. This is easily done with oil fuel. Neither economizers nor superheaters will be used.

In connection with the plant will be installed heat storage, consisting of vertical steel cylinders containing water under a temperature due to 200 lb. steam pressure, thoroughly protected with heat-insulating material. The water and steam spaces of these cylinders will be connected with the boilers through automatic stop valves which will open whenever the pressure in the boilers is greater than in the heat storage cylinders. In the heat storage cylinders will be installed internal electric heaters having capacity sufficient to maintain the temperature of the water in them, or, in other words, to supply the heat losses from radiation and convection. The capacity of these heat-storage cylinders to be such, that by reduction of the gauge pressure from 200 to 25 pounds, sufficient steam will be formed to operate the plant at full capacity for thirty minutes. All steam connections to be as short and direct as possible, and all precautions used to keep radiation and condensation losses at a minimum.

On the above assumptions, the following calculations are based:

Rated Horse Power of Boilers Required. The turbines will require at 12,500 kw. load with 175 lb. steam pressure, 28 in.

vacuum, and without superheat, 16.69 lb. of steam per kw-hr. To handle auxiliaries of the plant and the oil burners will require 10 per cent of that required for the main units, or the total maximum amount of steam per hour required will be 459,000 lb. This can be furnished by 11,475 rated h.p. of boilers, working at 33⅓ per cent overload. It is assumed that this boiler power will be installed in 16 units of 720 rated h.p. each.

The amount of heat storage required in connection with each of the above boiler units is calculated as follows:

When the pressure on water under a temperature due to 200 lb. steam pressure is reduced to 25 lb. about 13 per cent of the water will pass into steam at gradually reducing pressure. The assumption was made that the heat storage shall be capable of furnishing steam for the plant for 30 minutes at full load, or 229,500 lb. This is increased by 33⅓ per cent to allow for reduced economy of the turbines with the falling pressure, which calls for 229,500 plus 76,500, or 306,000 lb. As 13 per cent of the water in the storage cylinders passes into steam, they must contain 306,000 divided by 0.13, or 2,353,847 lb. Each of the 16 boiler units will, therefore, need 147,116 lb. of hot water in storage. Assuming the water to weigh 60 lb. per cubic foot at temperature due to 200 lb., the volume of the containers will be about 2800 cu. ft. This volume will be provided by one cylinder, 12 ft. in diameter by 26 ft. in length, allowing steam space over the water. Each of these cylinders will weigh approximately 120,000 lb., and will cost delivered and in place not to exceed 6½ cents per lb., or $7,800. Each storage cylinder will supply 1563 kw. of station capacity, or the cost of storage per kilowatt capacity of plant will be about $5.00. These figures are given to show that the cost is not prohibitive.

COMPARISONS

Comparison of First Costs. The cost of the gas-making station, as above outlined, is assumed as being $1,000,000, complete with buildings and storage. The figure is based on data procured within the past two years, and if in error, is possibly too low.

The cost of the electric generating station complete, including gas engines, generators, piping, switchboards, wiring, foundations and buildings will be approximately $2,250,000, based on recent quotations.

At these figures, the cost per kilowatt capacity of station for combined gas and electric plant will be $130 per kw.

The cost of the steam-turbine plant complete, including turbo-generators, boilers, heat-storage cylinders, piping, condensers, switchboard, wiring, foundations and building will not exceed $1,500,000, based on recent quotations. The cost per kilowatt capacity of station is, therefore, $60.

The steam-turbine station cost is approximately 46 per cent of that of the gas-engine station.

Comparison as to Rapidity of Getting into Operation on the Line. It has been demonstrated in the Martin Gas-engine station, previously referred to, that one of the large engines can be brought up to speed, its generator synchronized, and connected to the line in 30 seconds. In order that this may be done, however, the operator must be at his station when the signal is given. In the station assumed, 12 engine operators would be required, each at his post, all equally trained to accomplish this, and probably an equal number of switchboard operators. Even then, difficulties in synchronizing such a number of machines simultaneously would probably take a longer time. The expense of keeping such a large operating force as this calls for, is too great to be feasible, and I assume that each operator will handle two engines, and that he will get the two generators on the line in two minutes. I should consider it exceptional work if the entire station could be in operation on the line in two minutes.

In the case of the steam-turbine plant, the following sequence of operations would be followed: The turbo-generators would be operating on the line as synchronous motors to assist in regulating power factor, and with vacuum maintained on the steam ends, with the air pump operating. Steam would be in the main line up to the throttle valves, also on oil-burner line. If current on the line fails, the rotors of the units will continue to revolve for many minutes. Immediately on notice, the operator will begin opening his throttle valves, and energizing his fields from a storage battery, and could easily synchronize the two machines and get on the line within less than two minutes. The air pump, if operated during the period of starting from the storage battery, would require no attention, and if a jet condenser is used, the only requirement in connection with circulating water is that the injection valve shall be opened.

Concurrently with the above, the boiler-room operator will release and open all boiler dampers at one operation, and from the same central point put steam and oil on all burners, and by the use of electric igniters start fires under all boilers simultaneously. The steam pressure in the heat-storage cylinders will gradually fall until at the end of 30 minutes it will have reached 25 lb. By the expiration of that time, the boilers can be brought to steaming condition under a pressure of 25 lb. or more, and will pick up the load.

I consider that I have reasonably established the fact that the steam-turbine station can be put on the line as promptly as the gas-engine station.

Comparison as to Stand-by Charges. I shall consider this on the basis of the annual stand-by charge per kilowatt of capacity of plant.

Assuming that the fixed charges of interest, depreciation and taxes will amount to 10 per cent which favors the gas-engine plant, the annual charge against the gas-engine plant will be $13 per kw. and $6 against the steam-turbine plant.

I will assume that the gas-engine station proper can be taken care of by two crews of six men each at the engines, and two at the switchboard, which is certainly more than fair to it. These men will get not less than $100 per month, or an annual pay roll for station of $19,200.

The gas-making plant will also require two crews, each assumed to require six men which number is an absolute minimum. Their average wages will be not less than $100 per month or an annual pay roll of $14,400. The combined pay rolls will be $33,600, or an annual charge ot $1.34 per kilowatt of capacity.

To keep the gas-generating plant in condition such that it can begin making gas with a reasonable degree of promptness. the generators must be kept fairly hot, which will require expenditure of fuel. I have no data of my own as to the fuel necessary for this purpose. Mr. E. C. Jones, chief engineer of the Pacific Gas and Electric Co., informs me that with an expenditure of 150 gal. of oil per day, it is possible to keep a 2,500,000 cubic-foot oil-gas set, at a temperature such that it can be brought to condition for commencing to make gas in 20 minutes. Three such sets will, therefore, take 450 gal. per day. The annual stand-by fuel charge, oil being figured at $1.00 per barrel, will amount to $3,911, or 16 cents per kilowatt of capacity.

It is assumed that the steam-turbine station will require two crews, each composed of the following; two turbine operators, one switchboard man and two firemen. The average monthly wage is taken at $100 per month, which would make the annual pay roll $12,000. or 48 cents per kilowatt of capacity. The heat-storage cylinders will be covered with extra thick heat insulating covering, around which will be built an enclosing shell of brickwork. It is assumed that the heat losses per square foot of shell, per fahr. degree difference of temperature per hour, will not exceed 0.1 B.t.u. The total surface of all heat storage proposed is 37,728 sq. ft. With a temperature of external air of 70 degrees fahr., the heat loss per hour will be 689,790 B.t.u. The main steam piping that will be under steam will have a surface area of not to exceed 3,500 sq. ft. The loss from this surface is taken as 0.2 B.t.u. per degree difference of temperature per hour, or a total loss on account of such surface of 221,900 B.t.u. The combined loss of 911,690 B.t.u. is equivalent to 359 h.p-hr., or 270 kw-hr.

In other words, it will only be necessary to use a little over 1 per cent of the capacity of the plant to keep the heat storage and main steam pipes up to temperature, as the electric heaters will transform the energy at practically 100 per cent efficiency. I think I may safely state that any of our hydroelectric plants have for at least 22 hr. per day energy going to waste in an amount much greater than 1.1 per cent of the peak load, and that under such circumstances the waste energy should not be considered a charge against the plant. The radiation losses, as above taken, would in two hours reduce the temperature of the water in storage less than one degree fahr., so if no waste energy were available for two hours daily, the effect so far as the value of the heat storage is concerned would be negligible. The original heating of the water, and restoration of temperature of the water in the storage cylinders after a run would be accomplished by the use of steam from the main boilers.

It is assumed that steam will be kept on one 300 h.p. boiler, to operate pumps, to supply steam to burner lines and as an emergency precaution. An allowance of 450 gal per day will maintain pressure on this boiler, and permit the use of 1000 lb. of steam per hour, and at $1.00 per barrel will amount to a yearly charge of $3911, or 16 cents per kilowatt of capacity.

The stand-by charges per kilowatt capacity of the two plants will be as follows:

	Gas engines	Turbines
Fixed charges	$13.00	$6.00
Pay rolls	1.34	0.48
Fuel used	0.16	0.16
Total stand-by charges	$14.50	$6.64

The stand-by charges for the turbine plant are less than 46 per cent of those for the gas-engine plant.

It would be entirely legitimate to make a small charge against the gas-making plant for maintaining steam on one of its boilers, but this has been neglected in the above.

If the entire loss of heat from storage cylinders and piping were made good from the auxiliary boiler, the annual fuel charge for this service would not exceed $2,000.

I believe the above discussion proves my statement that the stand-by losses of the turbine station will be less than for the gas-engine station.

Comparison as to Costs of Continuous Operation. If I have been correctly informed, the manufacturers of the large gas engines at the Martin station, previously referred to, guaranteed them to deliver a brake horse power-hour on 18 cu. ft. of oil gas. No data as to the results acutally obtained have ever been given out, but from such information as I have been able to get, I do not believe that the results are any better than those indicated above.

From a paper read before the Detroit meeting of the American Gas Institute by Mr. E. C. Jones, chief engineer of the Pacific Gas and Electric Co., in October, 1909, I take the following data:

There will be required 8½ gal. of crude oil to produce 1000 cu. ft. of gas, and from the process of manufacture there will be a by-product of 20 lb. of dry lampblack per 1000 ft. of gas made, which should be credited to the gas-making process. A portion of the lampblack will be required for generating steam used in the manufacturing process. It is impossible by any method of treatment so far found economically practicable, to reduce the moisture content much below 25 per cent and it is generally fired when containing at least this much moisture. I assume that at least five of the 20 lb. will be used for generating steam, leaving 15 lb. to be credited.

There is no way in which this lampblack can be used in the plant outlined herein for gas-making, although water gas apparatus could be installed to utilize it Mr. Jones in the article previously cited, states that using the lampblack in water gas apparatus, 40 lb. wet lamp-black (30 lb. dry) will make 1000 cu. ft., using 6.8 gal. of oil for enriching. As 8⅓ gal. of oil are used for 1000 cu. ft. of gas under the straight oil gas process, each 30 lb. of lampblack saves 1.53 gal. of oil, or for the 15 lb. excess produced in making 1000 ft. of oil gas, 0.77 gal. In order to give the gas-making process every credit it can be entitled to, I deduct this 0.77 gal. from the 8⅓ gal., leaving 7.56 gal. net, chargeable to each 1000 cubic feet of gas made.

If the generator efficiency is 95 per cent, and 18 cu. ft. of gas are used per brake horse power, the amount used per kilowatt hour will be 25.24 cu. ft. The number of kilowatt hours per barrel of oil, from the data above, is 220.1.

To arrive at the kilowatt hours at the switchboard per barrel of oil in the steam-turbine plant, the following assumptions are made: That the average load-factor on the turbines will be 75 per cent when in operation; that the auxiliaries of the plant will require 10 per cent of the steam taken by the main units; that the evaporation of water will be at the rate of 12 lb. per lb. of oil.

The turbine assumed, is one where the steam consumption at three-fourths load will be no greater than at full load, or 16.69 lb. per kilowatt hour. Adding 10 per cent for auxiliaries gives 18.36 lb. of steam required per kilowatt-hour, or at the evaporation assumed, 1.53 lb. of oil. The oil weighs 336 lb. per bbl., and the number of kilowatt hours per bbl. of oil will be 219.6 as against 220.1 for the gas engine. Attendance and fixed charges have been previously shown to be less in the case of the steam plant, so I consider that I have established the remaining statement as to economy made in the earlier part of this paper.

I have endeavored in the argument made to use data and assumptions that in all cases favor the gas-engine station, and feel that on this score I have opened the door to criticism by proponents of steam plants for this class of service.

In closing, I cannot refrain from calling attention to the desirability of fuller information relative to the gas engine station at Martin, which I have previously cited. Judging from current reports it does not seem to have been an entire success. It is said that it is still in the contractor's hands, five years after installation, and that the purchasing company has abandoned it so far as use is concerned. Nothing has ever been published regarding its difficulties and troubles nor as to its economic results, and I hope that in the discussion of this paper those who know the facts will give the engineering profession the benefit of them.

DISCUSSION ON "EMERGENCY GENERATING STATIONS FOR SERVICE IN CONNECTION WITH HYDROELECTRIC TRANSMISSION PLANTS UNDER PACIFIC COAST CONDITIONS." SAN FRANCISCO, CAL., MAY 5, 1910.

President Stillwell: Accepting the reasoning of this paper, it would seem unquestionable that in this case the installation of large gas engine units instead of steam turbine units, was a blunder. The paper can be criticized fairly, I think, in respect to some details of the assumptions upon which its estimates are based. For example, I think that if the auxiliary plant is intended not only to be operated for a short time, in the case of an interruption in the transmission service, and also to be used in conjunction with the transmission of power in case of low water, the unit chosen is too large. The modification, however, that would result from changing the size of the turbines would not affect very materially the annual stand-by charges of the two plants.

L. Jorgensen: Nearly all water power companies of importance have found it necessary to keep auxiliary power plants in their greatest load centers, especially if these are large cities. The units in these plants are mostly steam driven, and, in order to be in readiness for service, part of the boilers are kept under steam at all times.

The expense connected with keeping the boilers under steam is considered to be of less importance than the additional assurance against long interruptions of service. Mr. Hunt has brought out a new device which promises to do away with the necessity of keeping the boilers under fire. This idea seems very simple and possible of application. Where real estate is high, there may be some objections to the extra space required for the heat storage cylinders, as these cannot be installed anywhere, but will have to be located near the boilers, in order not to complicate the steam piping too much.

The space, however, occupied by a plant of this kind will always be less than that required for a gas engine station. Where space water power is available during the greatest part of the 24 hours, electric heaters seem to be very appropriate for compensating for the radiating losses, otherwise it would seem to be more efficient to use super-heated steam (or saturated steam) from the 300 h.p. boiler kept under steam continuously.

Mr. Hunt is very conservative when he allows 33⅓ per cent for reduced economy in the turbine. It is true that with steam at 25 lb. gauge, expanding to 28 in. vacuum, about 33 per cent less energy is given off, than with steam expanding from 175 lb. gauge to 28 in. vacuum. Therefore, the actual loss would be the average loss, or 16.5 per cent. The turbine should lose but very little in mechanical efficiency if a few tricks are used.

Suppose the steam turbine is a five-stage impulse turbine designed for best economy at 150 lb. gauge pressure at the throttle.

This turbine will still have a high efficiency when working with steam of 175 lb. and 125 lb. pressure. At about 75 lb. pressure the first stage cannot be used any longer and must be by-passed. At this pressure the steam has twice the volume, and, therefore, only about one-half the weight per unit volume as at 175 lb. The energy of the flowing steam is $\frac{m}{2}v^2$ and as the mass at 75 lb. is only half that at 175 lb., the nozzles in the first stage are not big enough to let a sufficient quantity of steam through to pull full load and cannot be made big enough if the velocities of steam are to be right. The velocity v must be kept practically constant, in order not to lose in mechanical efficiency, as all the different blade angles are only correct for one value of v. Cutting out the first stage means a loss of about one-fifth in efficiency, but this loss has already been allowed in the 33 per cent. As further expansion takes place and the throttle pressure approaches 25 lb. it becomes more difficult to keep the velocities in the remaining stages at their correct value. It will perhaps be necessary to work the pumps somewhat harder to increase the vacuum ¼ in. or so, not so much for the extra power derived therefrom, as this would probably be used by the pumps, but in order to keep the velocity of the steam through the different stages at its proper value. In this way the turbine will not lose perceptibly in efficiency through the whole performance.

K. G. Dunn: I think there should be a further explanation made regarding the title of the paper. This should state that it is under Pacific coast conditions, and it should also state under our present knowledge of gas manufacture.

It is unquestionably true that the thermal efficiency of the gas engine is much higher than the thermal efficiency of any prime mover, therefore, it seems rather paradoxical to state that the efficiency of the steam plant is higher than that of the gas plant.

When we start with fuel, oil, and contemplate that 8½ gallons of oil are required for 1000 ft. of gas, we have a gas generator efficiency of approximately 50 per cent, while a boiler efficiency of 75 per cent with fuel oil is easily maintained, and in that fact lies the increased efficiency of a steam plant over the gas engine plant. I think the estimates are conservative for the gas engine plant. With high hydrogen gas, it is impossible to obtain the economies stated in the paper.

There is another point which comes under the head of hot water storage, that we suggested for a plant something like five years ago, which was to put in electrical heaters in connection with each boiler, these heaters to be placed in circulating pipe, the action being similar to that of a house boiler. One of these heaters and circulating pipe would be connected to each individual boiler, and they could be left in service without interfering with the installation of the plant at all. There is a plant on the coast to-day that is making up designs and working this proposition, out, and unquestionably it will make a good proposition.

A few years ago, the transmission companies felt that auxiliary plants were not necessary, but in Los Angeles, San Francisco, Portland, Seattle, Spokane and all of the other large centers and congested districts on the Pacific Coast, each one of the operating companies has adopted the plan of installing a certain percentage of steam auxiliary plants to the total hydroelectric output, and unquestionably we will see developments along the lines as suggested in this paper very soon.

C. L. Cory: Mr. Hunt, in his consistent and careful manner, has with discrimination chosen the subject of the paper, namely, " Emergency Generating Stations for Service in Connection with Hydroelectric Transmission Plants under Pacific Coast Conditions." While what I may say in discussion has no direct application to the principal points in the paper, yet I trust it will have a general application to the subject.

Notwithstanding the definiteness with which the subject has been treated by Mr. Hunt, a man who has given much attention to the generation of power and the use of the gas engine, but who is more familiar with the power situation under eastern conditions than on the Pacific Coast, after reading Mr. Hunt's paper expressed some surprise that the conclusions of Mr. Hunt did not indicate that the gas engine has an important position in the large power generating station.

I have been fortunate in having discussed the application of the gas engine for the generation of electric power with the author of the paper and I wish to draw attention to some of the points showing the difference between the emergency station on the Pacific Coast and the general use of the gas engine as largely used in many eastern industrial plants.

A specific illustration given careful consideration within the past year will illustrate the difference between the conditions discussed by Mr. Hunt and those evidently assumed by the individual mentioned, who from his experience evidently has a great belief in the gas engine. The situation under consideration required the provision of a power plant having a total capacity of approximately 10,000 kw. for the operation of a large copper mine. It had been shown by careful investigation that the body of ore to be worked would keep the mine and mill continuously in operation for a period of not less than twenty years. At the power plant site California fuel oil costs $1.65 per barrel, this price being fixed by a 65-cent cost in the field plus freight. On the other hand, New Mexico coal could be obtained at a total cost of approximately $5 per ton, this figure being obtained by adding to the cost of the coal at the mine the freight to the power house site. The question to be decided was what kind of a plant to install, hydroelectric with transmission line, gas engine or steam driven units.

Ultimately without question there will be a hydroelectric plant installed to work in conjunction with the reserve plant at the mine, but what was under consideration at this time was the choice of type of reserve plant to install.

Upon careful investigation it was found that there were a great many places where gas plants are in successful operation, but none on the Pacific Coast using gas made from our California crude oil. Producer gas has not up to the present been made for large units from California oil. By producer gas I mean gas having a thermal value of from 150 to 200 B.t.u. per 100 cu. ft. If I understand the situation the gas used at the Martin station is the ordinary illuminating gas, having a heat value of from 600 to 650 B.t.u. per thousand feet. The quality of gas used in your gas engines will very materially affect the operation of the engines and the service derived therefrom.

In connection with the reserve station, in this particular instance of the 10,000-kw. plant for the copper mine, the distance of transmission would be approximately 60 miles, and as a result of three separate investigations the complete cost of such a hydroelectric plant would be $250 per kilowatt of station capacity, which would correspond to about $300 per kilowatt which could be delivered. The load factor on the plant will be between 90 and 95 per cent, and under such circumstances it would seem that the water power plant must be given very serious consideration. However, the reliability and continuity of operation in this instance were of such great consequence, as has been well indicated by Mr. Hunt, that the reserve steam station is now being built, and will be in operation before the hydroelectric plant can be completed.

In addition to the points that I desired to bring out regarding the distinction between conditions as set forth in the paper and existing on the Pacific Coast, and those conditions which are quite different where blast furnace gases or producer gas is used in many plants in the East, I have one question to ask in direct reference to the paper regarding the capacity of the steam turbines to continuously carry full load when the steam pressure drops to the comparatively low figure mentioned in the paper, or to question the capacity of the turbines and generators under such low steam pressure conditions to carry the full normal load.

L. L. Johnston: In selecting oil as the fuel to be used in several types of power plants of which comparisons are made, the steam turbo is immediately placed at considerable advantage over a gas engine plant in so far as costs of construction and operation are concerned. The abundance of low priced oil on the Pacific Coast, the high efficiency and capacity of steam boilers when oil fired and the very low first cost of an oil fired steam plant has compelled the adoption of oil as fuel and steam as the type of equipment for a plant in preference to all others.

The writer noted recently a large steam turbo-emergency plant near the city of Seattle within a few miles of coal mines and where coal is cheap. Yet this plant was fired with oil shipped from California.

It has been shown by estimate and experience that the gas engine can make the best showing only where fuels are comparatively expensive or where a low grade of coal or lignite must be used for fuel which gives poor results when fired under steam boilers but good results in gas producers. An oil gas producer has not yet been developed of sufficiently low cost and high efficiency to permit its adoption in connection with gas engines for general power purposes.

Considering the above, in discussing Mr. Hunt's paper, the most that can be shown in favor of the gas engine is that it can, under some conditions, do considerably better than set forth.

Regarding the size limit of gas engines having been reached in the largest units now in operation, it will be recalled that the same was said twenty years ago of 15 h.p. gas engines.

To-day there are several hundred thousand horse power capacity of large gas engines in the east. Most of these are in steel mills and in units of 3500 to 4500 h.p. capacity each. One of these units at Bessemer, Pa., has been operating continuously night and day for the past six months with a total loss of only three hours during that time.

Several experienced builders are now developing gas engine generator units of 5000 kw. capacity.

Some years ago when the Martin station was planned steam turbos of 12,500 kw. capacity there were not yet in commercial use. Also, the larger sizes which could have been selected were at that time going through a stage of development and giving more or less trouble, and the best ones required some minutes in which to be warmed, brought up to speed and put into service without damage to themselves. The gas engine had already demonstrated its ability to be put into service in a short time after standing cold.

Considering that the company owning the Martin station was already in the gas manufacturing business, that its gas equipment could be used in connection with gas engines, and with the other above facts in view, it seems logical therefore, that it should have selected gas engines to be used in its electric stand-by plant.

It has been remarked that the principal difficulty with the gas engines at the Martin station is caused by the high hydrogen content of the gas supplied, which has resulted in cracked cylinders.

However, gas engines are operating successfully at a plant in Lebanon, Pa., on coke over gas which contains a greater percentage of hydrogen than the oil gas at the Martin station.

Experience has shown that some designs of gas engines will operate successfully on a gas containing a comparatively large percentage of hydrogen while others will not. Also that some designs of gas engine cylinders will crack from various causes while others will not.

The fact that the gas engines at the Martin station have been in a state of overhaul so much of the time since their installation looks bad. However, inasmuch as the design of engines is different from the successful ones now operating in this country, the trouble must be laid to a design which has not yet been perfected. Had the engines been of the same design as those in the eastern steel mills, the results might have been quite different, the plant a welcome place to visitors and its merits discussed by engineers throughout the country.

Taking up the several comparisons in the order given by Mr. Hunt.

1. *Comparison of First Costs.* The first cost of the steam plant is favored in that it consists of only two large sized units. Should one of these become disabled only 50 per cent of the plant would remain for service. While in the gas plant about 92 per cent would remain should one unit become disabled.

It appears that the steam plant should have an additional turbo-unit to make it more comparable with the gas plant. On this basis the steam plant would cost approximately $72 per kw. of capacity on a 25,000-kw. rating.

Regarding the cost of the gas making station $1,000,000 appears rather high tension though the writer has no costs at hand to show otherwise. However, it must be remembered that the gas generating station of the Martin plant forms a part of the company's domestic gas manufacturing equipment and contains much apparatus, that would not be required in a strictly power gas plant. The gas generators there have a rated capacity of 3,500,000 cu. ft. of gas per day each and can be pushed to 4,000,000, or, each unit can supply gas for more than 9,000 B.h.p. capacity of engines. This large capacity of gas generator units should contribute toward a low first cost of the plant. These gas generators are simple in construction and consist principally of steel shells 16 ft. in diameter, lined with fire brick and filled with brick checker work.

Considering the fact that at the Martin station the gas plant forms a part of the company's domestic gas equipment and that several large gas holders and relay gas generators are necessary in any event, it will be seen that the first costs and operating charges against the gas engine plant can be materially reduced below those given.

Estimates have been prepared which show that large gas engine electric stations comprising engine generator units of the largest size used in the eastern steel mills, together with coal gas producers, can be constructed complete for $100 per kw. A similar plant but with oil gas producers, especially if constructed in connection with a domestic gas manufacturing plant should not cost more than $100 per kw.

Considering the above, the first cost of an oil fired steam plant would be approximately 72 per cent of that of an oil fired gas engine plant.

2. *Comparison as to Rapidity of Getting into Operation on the Line.* In this comparison it appears that the possibilities of the gas engine have been neglected.

Special consideration is given to the general design and appliances for the steam plant to facilitate its economical construction, operation and quick starting, namely; the plant is designed with only two large sized units; a storage battery supplies the exciter current. Heat storage tanks supply steam instantly, and an arrangement is devised by which all the boilers may be started simultaneously from a central point.

In order for the gas plant to maintain its record of starting in 30 seconds, it is pointed out that twelve engineers would be necessary, also an equal number of men at the switchboard.

There are several movements necessary to start a gas engine, all of which could be operated from a central point by a device similar to that described by Mr. Hunt, to be used in connection with his steam boiler plant, and all of the engines could be started and brought up to speed at the same time.

Regarding the problem of synchronizing a number of gas engine generator units, it is possible by having the exciting current flowing in several generators, to start them all and bring them up to speed in step. With this method of paralleling, combined with starting all units from a central point, it would be possible to start the entire plant as one unit and put it into service within 30 seconds and with a minimum of engine and switching labor.

3. *Comparison as to Standby Charges.* Based upon the foregoing figures it will be seen that the costs of a gas engine electric plant when operated in connection with a domestic gas manufacturing plant can be reduced considerably below Mr. Hunt's estimates.

4. *Comparison as to Costs of Continuous Operation.* Several years ago Mr. H. G. Stott, before a meeting of this Society in New York, called attention (TRANSACTIONS A.I.E.E. 1906), to the high economies possible to be obtained with a combined plant consisting of part steam and part gas equipment, so arranged that the waste heat from the gas part could be utilized toward generating steam for the steam part. The advantages in first cost and fuel economy of such a plant are so marked that it appears that any estimates for plants in which gas engines are considered, should cover this type of plant rather than a straight gas engine plant. The highest efficiencies attained in steam practice are accomplished largely by returning for use all possible waste B.t.us. with the assistance of economizers, feed water heaters, condensers, etc. Similar refinements in gas engine plants have not yet come into general use. However, they are being developed along the lines now followed in steam practice.

The oil gas generators at the Martin station are not as efficient thermally as they might be if designed especially for power purposes. Much heat is now wasted to the atmosphere in the process of heating the brick checker work and in cooling the gas which might be utilized in generating steam for auxiliary power uses.

The writer has prepared estimates showing comparative costs of a steam turbo plant and a combined steam and gas plant both using oil fuel. In the case of the combined plant it is assumed that the waste heat which can practicably be recovered from the gas engines and gas generators is delivered to the steam part of the plant in feed water. Also, that the lamp black resulting from gas making is burned under the boilers of the steam plant, together with the necessary fuel oil.

The assumptions are that each plant will contain 25,000 kw. capacity of equipment; the combined plant consisting of 15,000 kw. capacity of steam and 10,000 kw. of gas equipment. The combined plant is arranged so that the gas part runs continuously at nearly full load while the steam part handles the variable load and peaks. Also spare units would be included in the steam equipment.

The first cost of the steam equipment is taken at $65 per kw. and the gas at $115 per kw. on this basis the excess cost of the combined plant over the straight steam is $500,000.

The annual costs show that the combined plant can make a saving in the fuel item of $117,152 over that of the steam plant. However, on account of the higher fixed charges of the combined plant, the total annual net saving over the steam, amounts to only $55,153. This saving by the combined plant will pay 11.1 per cent interest on its excess cost.

This saving is perhaps not sufficient to warrant the construction of a combined plant under the conditions assumed. However, should a combined plant be constructed in connection with a gas manufacturing plant under conditions similar to those at Martin station, the first cost of the gas engine plant could be somewhat less than shown above. Also the labor charges against the gas engine plant would be somewhat less. Estimates for a combined plant on this basis, and assumptions similar to those above, taking the cost of the gas equipment at $105 per kw. and the steam at $65, show that the combined plant can be constructed for an excess cost of $400,000 and that its annual saving will amount to $73,000. This saving will pay 18 per cent on the excess cost. This should be sufficient to warrant the construction of such a plant and considering that this is based upon oil at $1.00 per bbl., which price may advance, there should be ample margin for safety in such a conclusion. Further economies could be obtained by returning to the power plant the waste heat from the gas manufacturing part of the plant.

The combined plant as estimated will give 266 kw-hr. per bbl. of oil.

While there are some conditions where steam turbo plants are obviously better suited, it would seem that all considerations of large fuel power plants should include a close investigation of the possibilities of the gas engine.

A. H. Babcock: It seems to me that in this gas engine discussion, as in many others of an engineering nature, we engineers are prone to look at the economies in a physical sense and not enough toward the economies in the financial sense. The court of last resort in regard to such things is the balance sheet.

Mr. Hunt, in his paper, has mentioned 650 B.t.u. gas as used in the engines in the hypothetical station he has constructed. It seems to me that his figures need a little revision in this particular, and that it will be safer to work with gas not quite so rich. When gas as rich as 600 or 700 heat units is ignited in an engine cylinder there is a real explosion, whereas producer gas of 130 or 150 heat units ignited in a cylinder gives a result more nearly in the nature of a push; the one is like dynamite, the other is like old fashioned black powder. We have heard a great deal about the high hydrogen content of the gas used in the Martin station engines as the origin of much of their trouble. It seems to me that the very rich quality of the gas has more to do with the difficulty than the hydrogen.

Mr. Johnson has been investigating gas engine projects on the West Coast for the last year, and is, therefore, especially qualified to have an opinion on them, particularly with reference to the economic side. He has found in many cases that while there are very cheap fuels available, and a high physical economy of the plant can be shown, the high first cost of the machinery and apparatus produces fixed charges so high that the physical economies of the processes are entirely wiped out, as far as the balance sheet is concerned. It seems to me that we are much in the same position with relation to our water plants, especially where there is more water in the securities than in the hydraulic systems, and it is my opinion that it is possible to construct a steam plant, oil fired, almost anywhere on San Francisco bay and compete successfully with the highly capitalized long distance transmission line power. I am aware that on many balance sheets the matter of fixed charges is not taken into account as it should be, and that reports made by engineers to financial men are misleading frequently in this respect. It is immaterial whether we ignore these fixed charges entirely, or whether we transfer them to the next generation, the fact is that they must be paid some time, and therefore it is misleading not to take them into account in our financial statements.

K. G. Dunn: I would like to call attention to one fact that should be taken into consideration when comparing gas engine plants with steam plants. In a gas engine plant, there is no possible overload capacity whatever. In the ordinary steam plant, each unit is capable of a continuous overload capacity of not less than 25 per cent, and it has a peak load capacity of 50 per cent overload. When you take the peak load capacity into consideration, it is unquestionably true that a steam plant can be installed for one-half the cost per kilowatt.

W. A. Doble: There is one point, Mr. President, I think should be brought out, and that is, that a gas engine or a reserve capacity plant of 24,000 kw. is extraordinarily large, and there are not so many transmission companies that would be justified in putting up a plant of that magnitude. It has occurred to me that the plant should be very much smaller than that, and though Mr. Hunt treats the matter very fairly, I do not think the paper shows clearly that under conditions of one-third or one-half that capacity, that these conditions would be favorable or as favorable.

There is another point with reference to putting in plants of this kind as against water transmission. It is interesting to know in this connection that the Pacific Oil and Power Company of Los Angeles which own its own oil wells, transmits power 129 miles and sells oil. It also uses some in its stations, and is now increasing the number of stations, because it is going into long distance transmission. If we consider a composite plant of steam and gas engines, and then a turbo-unit, I am afraid we would have to make a triple power plant, and then where would we be?

F. G. Baum: My criticism of Mr. Hunt's paper is, not in the conclusions, but in the method presented, which starts out like a debate or argument, presenting in the beginning the statement which it is intended to *maintain* rather than by presenting both sides of the question and then drawing the conclusions at the end. An engineer should be a judge and not an advocate and he should avoid being put in the position where he *must advocate* one side and not discuss and weigh both sides of a question with an open mind.

In both the gas electric and the steam electric plant we burn oil at one point and produce kilowatt-hours at another. But in the gas engine plant there are two inherent weaknesses in the process of developing power.

1. The process of making gas is intermittent.
2. The process of destroying the gas or changing it from gas to mechanical energy is intermittent.

In these two fundamental defects lie the inefficiency of the gas engine process of power development. As a general proposition, intermittent processes are inefficient because they waste more or less time, and because the time is wasted the machine must be larger, and because it is larger, it wastes more time, etc. Hence the cost of the machine increases and the waste time and its by-products become more and more a loss.

To make things efficient we make them "hum," that is, produce a constant *high speed* condition at each instant of time. That is what we do in the electric motor, the tangential or turbine water wheel, the centrifugal pump, the steam turbine, etc. Of all the power units the tangential water wheel driven generator is the simplest.

In the steam turbine process of developing power we have practically a constant condition at each point of the machine for each instant of time, and hence the mechanical conditions for efficiency are good. We also have conditions right for producing units of large capacity, which again is a very decided advantage over the gas engine unit. For constant power in large units (except under conditions where the gas engine burns waste gases) the steam turbine is far preferable to the gas engine and because we can make it " hum "—that is, get the advantage of high speed and constant power, it has certain inherent advantages over the reciprocating steam engine.

The disadvantage of the steam-electric unit for emergency purposes is the delay in getting up steam. Whether the scheme for steam storage outlined by Mr. Hunt is practical or not I do not know, but as he has proved his case on the assumption that it is practical, I presume he has had experience with the scheme. It is an easy matter to prove theoretically the gas engine highly efficient, but in the practice the results may be different; hence theoretical proofs must be backed up by practical results before they can be accepted as final."

President Stillwell: So far as this particular gas engine plant is concerned, Mr. Johnson's contribution to the discussion furnishes a clear and perhaps an adequate explanation. Not infrequently what apparently is a serious engineering blunder results from circumstances purely local and transitory, which properly exonerate the engineer from responsibility.

A. M. Hunt: It was not my intention in writing the paper to indicate in full detail and outline the design of a plant. The estimates have been made simply as a basis for comparison. As a matter of fact, each individual case would have to be considered upon its own merits, and worked out accordingly. I should, in all probability, in designing a station of this character, arrange it in such a way that the water in the boilers would be in circulation in connection with the heat storage, and my reason for not doing that in the paper was this: I had no data on which I could calculate or even approximate the radiation losses from the surface exposed in the boiler, so I cut that out as the easiest way of avoiding the point. Mr. Stillwell as well as several others, have referred to the fact that the steam turbine station is equipped with but two large units, which is not just in making the comparison. This, in a measure is true, but it is partially offset by the fact that in a gas making station, the gas generators are assumed as only three, so if one of them is out of use, one-third of the plant would be unavailable. It may be argued that the gas generator is a machine that does not work all the time. From time to time the gas generator must be shut down and allowed to cool off, the brick work re-set, and so forth; so that, as a matter of fact, in such a station, it might be considered that four gas generating units should be employed.

Mr. Jorgensen, in his remarks, speaks as if the heat storage proposition were a new element. It is not. I reca'l that back in the '90s, if not earlier, this question of heat storage was discussed in connection with generating stations in England by Mr. Halpine. He worked it out at some considerable length, but what application was ever made of it, I do not know. Mr. Stillwell, says that it was actually employed. In that instance, as my recollection serves me, it was intended to equalize the daily fluctuation of the load on the boiler plant and avoid the necessity of the installation of larger boiler capacity, and possibly getting also higher efficiency.

I am surprised that no one has taken exception to the fact of using the electric heater in the heat storage, although, I believe, some one did mention the fact, that he would prefer to maintain the temperature of the water by using steam from the auxiliary boiler. As a matter of fact, I admit that the electric heater is perhaps what might be called " finicky ", still it could be made of such elemental simplicity, that I believe its use would be justified, at least, in certain cases.

Mr. Jorgensen criticized the increased steam consumption of the turbine under reducing pressure, as being stated by me as too high. I do not recall the details of my calculation on this, and, in fact, I will say frankly, that it was a matter of guess as I first put it down, but subsequently I ran across one of the turbine designers and requested him to calculate it for me and he came back and said, " You are a very good guesser, I worked it out as about 32 per cent," so I let it stand.

Mr. Dunn has made some remark with reference to the efficiency of the gas making process as compared to the efficiency of the use of fuel in the boilers. It is quite true, in reference to the present method used in making gas from oil, and the present method is the only one at this time commercially operative. It is true that a number of people are working on the problem of making producer gas from oil, having a lower heat value, and a higher efficiency, and I know of at least two such processes that are in tentative commercial shape. I should not be surprised to see either of them developed in the near future to a point where they can be given serious consideration, and in such case, the gas engine side of the controversy would be at greater advantage.

Professor Cory, in his remarks, raises the query as to the possibility of the turbine keeping up and carrying the load at the reduced pressure. It is entirely possible, but would, of course, necessitate the turbine being especially designed for the end in view.

Mr. Johnson rather infers that I am not entirely fair to the gas engine in taking oil as the fuel for my basis of operation, and yet under conditions as they exist here on the Pacific Coast, oil is, of necessity, the economical fuel.

Mr. Babcock left the inference that he may have something up his sleeve in the way of near-at-hand supply of fuel.

believe I know myself of certain "pseudo" coal mines in the near vicinity, but I should be afraid to offer any consumer the coal from them.

Mr. Johnson also attempts to smooth down the criticism with reference to the installation of gas engines as the Martin station. It is to be regretted that he must be the one to stand up for the station, but when he states that the gas engines were adopted because they were installed in connection with the gas plant, with which they were manufacturing gas for domestic and other purposes, here, I think he is wrong. I do not think Mr. Johnson was on this coast at the time that plant was installed. That plant was installed, if my information is correct, because it was a necessity at that time, under the conditions of a contract made for the supplying by the Pacific Gas & Electric Company, or its predecessors in interest, that a plant should be installed which would be capable of being started within a given interval of time, and put current on the line, as a guarantee that continuity of service would be afforded. It was not installed to make gas for domestic or other purposes. It was installed solely and purely for power purposes. It is true that if it were installed in connection with a gas manufacturing plant for domestic service, the unit of cost would perhaps be somewhat reduced; but this was not the case in the instance I have in mind. You cannot build a plant and use it both for power service and for domestic service. If the plant is devoted to power service, it must be held for that, and not at any time used on domestic service, except in case of ultimate emergency.

Mr. Babcock takes some exception to my having made the comparison on the basis of gas having such high heat value. I do not know how he would make a gas of lower heat value out of crude petroleum by any present operative process. As I have stated, there are processes in line of development to-day that may lead to that outcome.

Mr. Doble's criticism as to the size of the plant selected for the purpose of comparison is entirely just. There are few plants in existence on the coast that I know of where a 25,000-kw. emergency plant would be justified, but at the same time I do not think the legitimacy of the argument, or the result, would be very much different, even though the size of the plant were quite materially reduced.

Cary T. Hutchinson (by letter): Mr. Hunt justly says of water-power plants, "*absolute* continuity of service is a thing which cannot be secured." This might also be said with equal truth with regard to steam plants or any other kind of machinery. His opinion evidently is that a stand-by steam plant is necessary in order to secure *satisfactory* continuity of service, and that this plant is required principally to guard against failures of machinery, including transmission lines, and not primarily to make up the deficiency in the water supply.

Mr. Hunt proposes a plan which does not by any means secure "absolute" continuity of service; in fact, it does not provide for as great continuity of service as can be provided by a steam plant. He seeks to lessen the cost of the stand-by service and to this end proposes hot water storage under pressure, arrangements by which the labor is minimized and certain other devices all tending to this, but all on the other hand diminishing somewhat the degree of insurance secured. A steam plant for the most effective stand-by service should have pressure in all the boilers, up to the throttle, auxiliaries in operation and fields of generator excited—indeed, one might even say that the generators themselves should be turning over. The plant also should be practically fully manned, and should have the same capacity as the load for which it is a reserve. If this degree of insurance against interruptions is required, I think it can easily be shown that the most economical way to obtain it is not to build the hydroelectric plant.

The investment cost of such a hydroelectric plant including substation, but not including distribution lines, will certainly be $200 per kilowatt of delivered power and probably greater, say, $250. The total annual cost per kilowatt of plant capacity will be at least $22 and probably more, including interest, depreciation, maintenance and operating expenses. A reserve steam plant of equal capacity, of large units, (and this is the only kind of plant that I am considering) can be installed complete for not more than $75 per kilowatt. The total stand-by charges against this plant, including all fixed charges, maintenance, labor and such fuel as is necessary to keep it in instant readiness for operation, based on a number of detailed estimates made by persons familiar with the conditions of the Pacific Coast, will be approximately as follows, per kilowatt of capacity:

1. Fixed charges	$10.00
2. Labor	2.50
3. Fuel and Supplies	2.50
Total	$15.00

But whatever this amount may be, it is a charge which will remain unchanged if the same plant is used for service instead of used as a stand-by plant. With oil as fuel, the cost of generating energy over and above the stand-by charges already referred to will not exceed 4.5 mils per kilowatt-hour. For an additional expenditure of $22 the steam plant can be operated on a load factor of 4880 hours, that is, approximately 56 per cent, for the same total annual cost. There will furthermore be a saving in the investment cost of $200 per kilowatt; that is, the same gross and net earnings can be obtained for $75 per kilowatt instead of $275 per kilowatt, in other words, the investment for the same gross earnings is reduced to less than 30 per cent.

I think it is safe to say that no competent engineer could possibly advise the construction of a steam plant as a stand-by station under these conditions, which apply pretty closely to the Pacific Coast.

If such a high degree of insurance against interruptions is not required, the next question that arises is the best way to obtain what might be called "satisfactory" insurance of commercial operation. This could be accomplished in several ways, one being to install a steam plant of lesser capacity than the total, say, 50 per cent; but in this case, of course, there would remain considerable interruptions to service. It is doubtful whether the additional cost involved in a steam plant of 50 per cent capacity for stand-by service only, is justified, and it would seem that the better way is to build a hydroelectric plant without steam reserve of any kind, but in the most permanent way possible, eliminating flumes as far as possible, constructing tunnels wherever feasible, and using reserve generating sets and duplicate transmission lines, preferably on entirely independent rights of way. The records of the Stanislaus transmission would seem to indicate that when properly constructed and maintained such a transmission line on the Pacific Coast is very nearly free from interruptions. If two such lines were built on independent rights of way, the service in as far as this part of the plant is concerned, would certainly be satisfactory.

It is fairly certain, however, that no water-way composed largely of flume can be built that will not give continuous trouble; tunnelling should be resorted to wherever possible. This is dictated not only by reliability of service but also by economical considerations, in many cases, inasmuch as the total annual charges against the flume line, including maintenance and depreciation will frequently exceed those of a tunnel to take its place, as the following example, which is fairly typical, indicates.

A flume line having a capacity of 200 second-feet, probably would cost under average conditions $30,000 per mile. The annual cost of this line for interest, depreciation and maintenance would be not less than $6000 and might be as high as $7,500 per mile. A tunnel of this capacity, concrete lined, could be built for approximately $100,000 per mile; its maintenance and interest would be, say, $6000. The tunnel is, therefore, as cheap, mile for mile, as the flume, but in many cases one mile of tunnel will replace several miles of flume, and the advantage of the tunnel is much greater.

It would seem to me that the best engineering solution of this problem is then to build the hydroelectric plant in the most substantial manner possible, to construct reservoirs of the maximum possible capacity, in order that the water power may be utilized at a load factor of 100 per cent or as near this as it is feasible to bring it, and then to supplement the delivery of the water power plant by a steam plant at the point of consumption which acts as a stand-by plant to the extent of its capacity and also as a peak load plant under daily service conditions. It seems folly to build a steam plant for stand-by service pure and simple when by comparatively small addition to the annual cost this plant can be used to bring in a large amount of additional business.

The following comparison between the cost of a system of reservoirs to utilize the drainage area to the fullest extent and of a steam plant to make up the deficiencies in the water supply is fairly representative of the Pacific Coast conditions:

Precipitation	60 in.
Runoff, 55 per cent = 2.44 sec. ft. =	33 "
Assume development for 2.2 sec. ft. =	30 "
Runoff for six low water months, 0.45 sec. ft	3 "
Runoff for six flood months	30 "
Use for power during six flood months	15 "
Storage during six flood months	15 "
Needed for power during six low water months	12 "
Remainder lost in evaporation and seepage	3 "
Storage 15 in. equal 35,000,000 cu. ft. per sq. mi	
Drainage area	250 sq. mi.
Total reservoir capacity	8,750 million cu. ft.
Cost of reservoirs, at $200 per million	$1,750,000
Total annual charges, at 6 per cent	$105,000
Head	1,200 ft.
Average flow, 250 × 2.2 sec. ft. =	550 sec. ft.
Average delivered power at sub-station	33,000 kw.
Load factor	50 per cent
Capacity of sub-station	66,000 kw.
Low month discharge, 250 × 0.45	112 sec. ft.
Low month, discharge, of average	20 per cent
Steam plant capacity (say 75 per cent)	50,000 kw.
Cost of steam plant	$3,750,000
Annual cost of stand-by service	$750,000

That is to say, if it were possible to construct reservoirs of sufficient capacity, the entire runoff from this drainage area could be utilized at an investment cost of $1,750,000, and an annual cost of $105,000, as against an investment of $3,750,000 for the equivalent steam plant, and an annual cost of $750,000, a saving of $2,000,000 in investment and of $645,000 in annual charges.

P. H. Thomas. In his heat storage steam relay arrangement Mr. Hunt has given an ingenious and in one sense a feasible plan for maintaining an uninterrupted supply of power on a distribution system. This general subject of relays in power systems is receiving a good deal of attention at the present time and, as seems to be usual under similar circumstances, engineers are inclined to take an extreme view, some one way and some the other. It is the opinion of the writer, however, that the wisdom of the installation of a steam relay plant is not one to be settled off hand without a careful study of the conditions of any particular case. There are cases of course where such relay is imperative but there are also many cases where it would not be warranted.

The absolute necessity of a local relay arises with some sorts of load, as mine pumps, hoists and some work in connection with furnaces of various sorts, but these are exceptional forms of load, and furthermore are usually service for which a relatively high price for power is obtained. With other systems however, the dominating consideration is different, namely, is that of economy, on account of competing power. In these cases, usually, an occasional interruption, while perhaps excessively annoying, is not a source of very great actual expense either to the company or to the consumer. Of course frequent interruptions have a serious harmful effect on the sales of power. At the present time the standard of our best transmission plants, after the initial starting and trying out periods is good. It must not be forgotten also, that no form of alternative power is entirely free from interruption so that relative excellence is all that is required. It is obvious that the extra investment required by the relay may be very considerable.

It will frequently be found that the real necessity for a steam relay exists only for some few customers so that a relatively small relay will suffice. Such a condition is not so serious. Again the same reliability may be sometimes attained by some alternative method. The high class engineer's most necessary quality, his sense of proportion, should here come into requisition. I do not here wish to be understood as decrying steam relays broadly but merely to call attention to some to their disadvantages and limitations.

What can actually be expected of a steam relay in the matter of preventing all interruption of service? Take the case where the relay is within a few hundred feet of the consumer who is to be protected. If the relay generator is not on the line there will be a certain brief interruption in case of a sudden failure of the main supply, long enough to get the generator on the line and the boilers steaming at their proper rate. If the generator is floating on the line there will still occur the equivalent of a partial shut down for the boilers which have been banked cannot be momentarily forced to give full steam capacity, without some such storage devise as is proposed by Mr. Hunt. Again if the trouble is one that causes a short circuit or a ground it may open the steam generator breakers or otherwise momentarily prevent its taking up the load. Even in the case of successful automatic circuit breakers there will usually be drop enough in voltage from a good short to throw out any synchronous apparatus on the consumers circuits.

Taking the case where the system is one of distribution at high potential as well as transmission, as is the case in most hydroelectric systems, there will be only one consumer who will get the full protection of such a relay since the others must be fed through some portion of the high tension line and trouble on this portion will cut off the relay.

It is thus clear that only in a few cases will it be possible, by means of a relay entirely to prevent *momentary* interruptions of a consumer's supply and in these actual success would be secured only by the best of upkeep and concentration of effort on this one result.

When, however the elimination of interruptions of the service of some considerable duration is considered, the case assumes a very different aspect. A steam turbine and banked or even cold boilers can be gotten into service and onto the line in less than perhaps an hour, and sometimes much sooner, if planned and operated for this purpose. That is as protection against interruptions caused by serious accidents that more or less permanently disable some part of the supply system and that consequently require time for repair, the banked boiler steam relay will serve admirably, except of course for cases where the injury interrupts the communication between the relay and the consumer. For momentary interruptions on the other hand such as flash-overs on line insulators where no permanent injury is done, the service can be re-established on the original circuits more quickly than a new set of operators can get it started on a new set of circuits.

On the side of the advantages of the steam relay there is much to be said. A system provided with a steam relay is usually much more flexible in operation as well as having the direct advantage of possibility of using the *relay power on regular load*. In fact the most satisfactory basis for the installation of a steam relay is the rendering possible thereby of the sale of increased total power. The well known curve of flow of many streams showing a sharp minimum for a relatively short period of the year, far below the average, limits the maximum sale of power, while with a steam plant supplementing the low water, a much larger sale is possible, supplied nearly all the year around by the hydraulic apparatus. In this well known case the great limitation of the steam relay, its extra cost, is partially obviated, for the output of extra generating capacity in the hydraulic apparatus, which takes the steam load most of the year will not usually add anywhere nearly proportionally to the capital cost. This is the natural use of the steam relay. But in such a case it has in one sense ceased to be strictly a relay, but is rather a supplementary source of power. It will have the strict relay function, however, at times of plentiful hydraulic power.

While every case must depend on its particular circumstances, it is clear that for reasons of capital costs a *steam* relay, at least where no supplementary power is produced, should be installed only where very strong reasons exist therefore. Suppose, for example, that the relay plant installation costs per kw. one half as much as the hydraulic development. This means that 50 per cent will be added to the fixed charges of the hydraulic system, which constitute the chief expense charges of such a system. But more, the expense of banked fires, trying out the steam apparatus periodically as well as the maintenance of at least the skeleton of a steam organization, will add very greatly to the small operating expenses of the hydraulic plant. When it is remembered that the added reliability of service will add little or nothing to the price to be obtained for power, the hand-cap in the dividend paying possibilities of the plant due to the steam relay are evident. It should be remembered, that exception is to be made in the case of steam relays which supplement a minimum hydraulic power and hence justify their added capital charge by increased sale of power and in the case of mining plants and other plants where a very difficult transmission exists and exceptionally high prices can be obtained for power and practically absolutely uninterrupted services is essential.

This discussion so far is not intended to minimize the importance of reliable service, but is preparatory to raising the question whether some other better way cannot be found to serve the same purpose.

In the first place in important work it is necessary to use only structures and apparatus that are substantial and reliable. No amount of relay will compensate for inferior construction. In the second place alternative lines and apparatus all through a system must be provided, for the purposes of inspection and repairs if for nothing else. Any unit must be spared when necessary. To reduce this additional cost of the spare capacity thus required, the units should be several in number so that the duplication of one unit will not be a large percentage of the total. This applies both to transmission lines and generating stations. Thus the real essential is to have several generating stations of the most available sort rather than one hydraulic and a steam station.

With at least two hydraulic generating stations and duplicate transmission lines following different routes most of the essential *relay* advantages of the steam relay are obtained and the duplicate or spare apparatus forms a part of the regularly effective elements of the system. As long as it is not practicable at most points of the system to absolutely eliminate *momentary* shut downs, even with a steam relay, it is the opinion of the author that in general, with the exceptions already noted, the first effort should be directed toward securing the necessary reliability through good construction and a number of hydraulic stations and duplicate lines following separate routes, if possible, rather than to suffer the duplication of capital in a steam station, to be *used purely as an emergency relay*.

Additional exceptions may be made where a single consumer is given a special relay of relatively small power or where personalities of some sort enter or a steam station is already in existence and can be obtained at small cost.

Mention should be made of the extreme importance of strict discipline and careful organization and planning in advance the procedure to be followed in case of trouble, as well as intelligent superintendence, in actually realizing reliable service.

It should also be remembered that exceptional freshets, land slides, earthquakes, tc., are rather "acts of God" than preventable accidents and are beyond the responsibility of the generating plant and it is not perhaps necessary or wise to permanently raise the power rates on account of the reserve apparatus capital charges necessary to forstal such catastrophies, especially as they may occur in many and unforseen ways and to guard against all will be prohibitive or impossible. When the maximum load comes but a few hours in the year as frequently happens it is clear that at other times there is plenty of relay apparatus, thus substantially providing against accidents.

In the study of reliability of service, it will be well to put more thought and emphasis on the automatic relay apparatus for separating good from bad circuits and limiting the short circuit damage, for by these great benefit can be done the service at little expense.

To summarize, the purpose of the above discussion is to bring out the point that the real function of a steam relay is to supplement the supply of power so that more kw. can be sold; and that emergency alternative service will best come from the use of several power houses of the most available sort and transmission lines following different routes and by providing spare units for each essential element.

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THE DEVELOPED HIGH TENSION NET-WORK OF A GENERAL POWER SYSTEM

BY PAUL M. DOWNING

The greatest incentive to the development and construction of hydroelectric transmission systems has been high fuel costs. This is particularly true in California, where, until the discovery of oil a few years ago, practically every industry using steam as a motive power had to depend on coal imported from Australia or British Columbia.

Owing, however, to the natural advantages due to the topography of the country, the possibilities of utilizing the waters for hydroelectric development were early recognized, and probably more has been done along pioneer lines in this state than anywhere else.

In the preparation of a paper on this subject, therefore, I have confined myself entirely to conditions as they have developed and as they exist in California at the present time, and to the experiences in connection with the different transmission systems, which together form probably the greatest mileage of high-tension net-work to be found anywhere in the world.

On account of the rapidly growing demand for power, it was not possible to wait for results, which, under ordinary conditions could have been obtained from actual operation, but, under the circumstances, things have been done which very conclusively confirm a statement made by Mr. Charles F. Scott in his paper on Electrical Power Transmission, read before the International Electric Congress held in St. Louis in 1904, wherein he states that problems of transmission are not problems that can be solved in the laboratory alone, but the apparatus must meet the precise conditions of operation and be judged by experience.

The first polyphase high-voltage transmission system in the world was the one from Mill Creek to Redlands, a distance of 16 miles. The original installation consisted of three 250-kw. three-phase generators delivering 2400 volts at their terminals, and seven 100-kw. transformers stepping up from 2400 volts to 11,000 volts at which potential power was transmitted to Redlands. The unqualified success of this undertaking almost from its very inception, gave a great impetus to the industry, and within a very few years other installations were made, each with its particular type of apparatus and character of construction.

The Colgate power house of the Pacific Gas & Electric Co. was really the nucleus of the present 60,000-volt net-work, in that it was the first to install apparatus to operate at that voltage, and it was, at the time, the largest and most important hydro-electric station in this part of the state. The history of this plant is unique, in that the generators were installed, in operation, and overloaded, before the construction work on the building was completed.

The system of the Pacific Gas & Electric Co. as it stands today represents the consolidation of a number of smaller companies, each with a system peculiar to itself, and none of them designed with a view of ever tying in with any other system. As a result, almost every type of apparatus from the comparatively small, low voltage, rotating-armature generators, to the larger, more modern, rotating-field, high-speed machines, is represented.

This Company controls and operates eleven different hydro-electric generating stations, having an aggregate capacity of 68,130 kw., distributed as follows:

Power house	Capacity in kilowatts	Generator voltage
De Sabla	13,000	2300
Centerville	6,400	2300
Colgate	14,200	2300
Yuba	660	2300
Alta	2,000	500
Auburn	500	500
Newcastle	800	500
Folsom	3,750	800
Electra	20,000	2300
Deer Creek	5,500	2300
Nevada	1,320	5500

Ten of these have a common frequency of 60 cycles and run in parallel on a 60,000-volt net-work which is also supplied with additional power from four independent companies.

The Great Western Power Co. delivers 60,000 volts by stepping down from its main line voltage of 100,000; the Sierra and San Francisco Power Co., the Northern California Power Co., and the Snow Mountain Power Co., deliver current at 60,000 volts direct.

At times, the load carried by these four companies amounts to an aggregate of 41,500 kw. In addition to the foregoing, we have the following reserve steam and gas engine plants which operate in parallel with the transmission lines when occasion requires; *viz.*, Oakland steam turbine station, San Jose steam station, and Martin gas engine station.

The total reserve capacity at these three stations amounts to 21,500 kw. In Martin station are located two 4,000-kw. frequency changers (from 60 to 25 cycles) which are operated from the transmission line. The 25-cycle side is run in parallel with the 25-cycle gas engine-driven units, and also with the 25-cycle steam-driven station of the United Railroads.

The entire mileage of lines represented by the different systems which are tied together, exclusive of those of 11,000 volts and under, amounts to 1,920 miles.

The voltages of the different lines making up the net work are as follows:

150 miles of 100,000-volt line.
1,390 miles of 60,000-volt line.
380 miles of 20,000-volt line.

It will be noted that lines of 11,000 volts and under are not included in the above for the reason that these lower voltage lines are considered as distributing lines and not as transmission lines.

The paralleling of stations in this manner, regardless of the length of line between them, or the loads carried, has not developed any difficulties, but on the contrary, it has been found that it could be done much more readily than where the generators are paralleled in the same station; nor is it customary to do this paralleling at generating stations alone, or on the low voltage side of sub-stations. As a matter of fact, it is done almost entirely on the 60,000-volt side, using transformers of relatively small capacity connected from line to ground for synchronizing purposes.

The governing and the division of load between the different stations furnishing power to a system of this kind is not as great a problem as it would at first appear. Each station, excepting one, takes its alloted portion of load and makes no attempt whatever to govern, unless the frequency varies beyond certain predetermined limits, the speed control being left entirely to a single station. All important power houses are equipped with governors, which, except in the case of the governing station, are set so that they will be sluggish in their action, and will not operate except on wide variations of speed. Those in the governing station should obviously be adjusted to regulate as closely as possible. The governing is not limited to any one particular station, but it can be done at any station having sufficient capacity to handle the fluctuations of load.

In order to operate, as we do, with a large number of stations running together, we found it necessary to have a chief operator, or what we have seen fit to call a "load dispatcher," who, so far as the details of operation are concerned, is in absolute charge of the entire system. Water cannot be taken out of a ditch or flume, a power house superintendent or foreman cannot shut down a generator or change the load carried on the station, and a line crew cannot work on a line, without first having the approval of the load dispatcher's office. He is at all times in direct telephone communication with every part of the system, and in the event of trouble which might interrupt service, has absolute control of all matters in connection with the re-establishing of service. In his office there is a board showing diagramatically every generating station, transmission line and sub-station on the system,together with dummy switches representing every air and oil switch, and the exact position of these switches, that is, whether open or closed. In addition to the record as shown by the board, a very complete log is kept of every detail in connection with troubles of any kind, loads carried by the different stations, and any other matters pertaining to operation.

Telephone circuits are run on all transmission lines, but these are not depended upon for anything more than local use, such as for linemen reporting on and off the line, etc. They do not give satisfactory service when used over long distances, and they become inoperative when there is trouble on the line and when they are most needed.

For communicating between important stations we have circuits leased from the telephone company, which run on its regular toll line leads, and being over entirely different routes are not affected to any extent by transmission troubles.

METHOD OF OPERATION

As stated above, the different stations are, for the greater part of the time, operated in parallel. There are two distinct advantages in operating in this manner:

1. The regulation of voltage is much more readily accomplished.
2. The capacities of the different stations can be utilized to their fullest extent.

On the other hand, there is a distinct disadvantage, as trouble on any part of the system will, to a certain extent, affect the entire system.

The inductive drop on the long lines forming a net-work of this kind is obviously high, especially where the induction motor load is heavy, and the power factor correspondingly low. The synchronous motor load represents a very small percentage of the entire load, and there is little opportunity to over-excite the fields and use them as boosters. The wattless current, therefore, becomes quite a problem, and has to be taken care of either by distributing it among the different power houses, or by taking it entirely on a single station, which can be handled very readily by proper adjustment of generator fields.

From an operating standpoint, and in order to better guarantee continuity of service to the more important districts, a reserve steam plant is very essential, and in this respect the modern steam turbine serves the purpose admirably. By reason of the fact that it operates equally well at all loads it can be connected in parallel with the transmission line, and under normal conditions will carry a good portion of the wattless current. At the same time it acts as a stand-by, and in case of line trouble it can pick up the load on very short notice.

Troubles on the long lines forming net-works such as this do not always seriously affect the entire system, but show only as momentary drops in voltage. The station generators are connected directly to the line, without circuit-breaking devices of any kind, and power is never cut off the lines unless it is impossible to keep it on. Immediately on the slightest indication of line trouble, the system is separated, leaving different sections or districts supplied from different sources. If the trouble is far enough removed from the generating station it will not be very severe on account of the inductive and ohmic drop of the intervening lines, and generally the operators will have time to separate the sections without more than a temporary drop in voltage. If, however, the trouble is near a power house, that particular station will be thrown out of synchronism with the system, and even the machines in that station may be thrown out of synchronism with each other.

CONNECTION

The greater number of the lines feeding into the system are supplied from transformers delta connected on the low-tension side and star connected on the high-tension side, with the neutral grounded.

This arrangement has proved very satisfactory, and while it might be said that there is a disadvantage in using such a connection on account of the grounding of one wire throwing a short-circuit on the system, yet there is a question as to whether or not this is a real disadvantage.

If all lines could be run through sparsely settled districts, or where there would be little liability of damage to persons or property were a wire to come down, there would, doubtless, be some advantage in operating with a delta connection, but where lines are run along public highways and through more or less thickly settled districts, it seems almost necessary that there should be some very positive indication to show when a wire goes down.

Some objection has at different times been raised by the telegraph and telephone companies to a grounded neutral system, on account of the inductive influences due to current through the ground, at times when the load is unbalanced. Experience, however, has shown that this is not the real cause of the trouble, but that the troubles these companies have are the result of what might be called static unbalance, or high-frequency disturbances due to arcing grounds, or other causes which occur to a greater extent in an ungrounded system than in one where the neutral is grounded, and therefore at zero potential. This statement is borne out by experiments that have been made on telephone circuits paralleling or carried upon the same poles as the transmission wires, where loads aggregating as high as 3,000 kw. have been transferred from three to two transformers of a bank, or vice versa, with practically no effect on the telephone service other than slight change in the tone of the line.

Our usual practice is, where one of three transformers in a bank at the generating end is out of service, to carry load up to the capacity of the other two, or should occasion demand, to over-load the two, making them carry the normal load of the three. It is not necessary to limit the unbalancing of power delivered to the line in this manner, and we would have no more hesitation in cutting out one of a bank of three 1500-kw. transformers than in cutting out one from a bank of three 100-kw. transformers. This same condition obtains in the case of step-down transformers. When the load to be supplied is small, and where the expense of installing three, or even two transformers to give a three-phase distribution would not be justified it is customary to install a single transformer, connecting it from the line wire to ground. Installations of this kind ordinarily give no trouble whatever, but work as satisfactorily as though a bank of three were installed. Careful attention must always be given to the ground connection. These are made by connecting to the water mains, and also to ground plates buried to a depth depending on the character of the soil.

Occasionally it has been found where only a single transformer is used, that a severe static stress occurs on the low-tension side, which is severe enough to puncture the insulation of the lower voltage transformers supplied from the main transformer. These instances, however, have been comparatively few, and while it is something which might be expected from a connection of this kind, it very seldom occurs, and it has never been serious enough to make it necessary to abandon the practice.

The connection on the low-tension side of the step-down transformers is either delta or Y, depending entirely on the particular voltage condition to be met. Where the Y connection is used, the neutral is grounded in the same manner as on the high-tension side, and to the same ground wire.

So far as the actual operation of the system is concerned, there is no preference as to the connection on the low side, but for economic reasons the greater number of low-tension distributing systems are supplied from the Y-connected transformer. We have never yet had any troubles which we could trace back and find to be the result of the manner in which transformers were connected.

TRANSFORMERS

The capacities of transformers used, range from 100 to 1500 kw. Most of them, except some of the smaller sizes, are shell type, oil-insulated, and water-cooled. The most satisfactory case for oil-cooled transformers is one of boiler iron mounted on a cast iron base and having a cast iron top.

A great deal of discussion has been heard concerning the merits of the different insulating materials used in transformers for high voltage work, the kind of oil to be used, and the methods of cooling the oil. During the past few years the tendency of the transformer manufacturers has been toward the use of a press board or horn fibre for the insulating barriers between the coils, this material being used to replace the micanite used in the earlier transformers. This gives a transformer of lower first cost but one correspondingly less staunch and reliable.

The micanite insulation has two distinct advantages; first, it will not absorb moisture as readily as the pressboard or horn fibre; and second, being non-inflammable, it will localize trouble, and a burn-out in one coil, unless it be exceptionally bad, will not damage adjacent coils. Until a few years ago all of the transformers on the system had micanite insulation. They would be received from the factory, and without attempting to dry them out, they would be filled with oil and put into service. The oil was generally shipped in iron drums containing from 50 to 100 gallons, and when received, it would be put into the transformer without treatment of any kind, and even without being tested to see that it had the proper dielectric strength. The pressboard has superseded the micanite, and the methods of handling transformers have entirely changed. We now find it necessary to dry them out thoroughly even after they have been standing without oil for not more than ten days or two weeks. The oil also is being handled much more carefully than formerly, and separate samples taken from the different tanks in which it is shipped, must be tested. If the dielectric strength is found to fall below a certain standard, it is safe to assume that the low insulating qualities are due to moisture, which can be readily removed by heating to a temperature slightly above 212 degrees fahr.

The pressboard or horn fibre will not only absorb moisture from the atmosphere, but it will, when in direct contact with water, absorb sufficient of it to allow the layers of fibre making up the sheet, to separate, thus rendering it worthless. This objection to its use might on first thought seem hardly worth considering, but in practice it is an important one. In handling transformers out of doors during stormy weather, or in the event of a damaged water coil allowing water to get into the winding, the pressboard would be damaged to such an extent that the transformer would have to be torn down and the barriers replaced.

As to the relative fire risks of air- and oil-cooled transformers, I think that it is now generally conceded that the oil type with a properly designed case is the safer of the two.

The greatest danger from an oil-insulated transformer is from fire external to the transformer itself, which might damage the case and allow the oil to escape.

In a number of instances there have occurred fires which have heated the boiler iron cases to such an extent that the oil has been badly carbonized and the paint on the inside of the case burned entirely off without damage being done to the winding. After removing the damaged oil and cleaning the winding, the transformers have been refilled with new oil and immediately put back into service without trouble. In one particular instance which I have in mind, a fire occurred in a wooden switch gallery almost directly over a bank of 700-kw., transformers which at the time were not in service. Before water could be turned on the fire the transformers had become very hot, and when water was finally turned on, the cast iron tops had become so hot that the water coming in contact with them, damaged them beyond repair. The windings of the transformers were uninjured, and after being dried out were put back into service and are operating to-day.

From the view point of the man who has to operate the transformer, particularly in connection with long high-voltage lines, I am inclined to question the advisability of attempting to sacrifice the reliability of the transformer in order to cut down the first cost. In the absence of any approved device or apparatus that can be relied upon to take care of high-voltage line disturbances, the transformer must bear this burden to a very great extent, and the breaking down of a transformer with the resulting interruption to service, will, in a very short time more than offset any saving in first cost. For this same reason the three-phase transformer is at a disadvantage, as trouble on one phase would entirely interrupt service, unless a spare were installed.

For cooling the oil we employ the usual method of circulating water through copper coils immersed in oil. Different metals have been used in these coils, but on account of there being less liability of copper being acted upon by acids in the cooling water, and also because of the fact that it will not corrode, it has been found most satisfactory. In localities where there is any great amount of mineral in the water, a cooling coil will in time become filled to such an extent that it will not carry a sufficient amount of water to cool the transformer. This deposit closely resembles boiler scale, and in some instances it can be removed by taking the coil out of the case and hammering it on the outside to loosen the scale, after which it can be blown out by either steam or compressed air. In cases where it cannot be removed in this way, we have used dilute muriatic acid as a last resort, but as this acts upon the metal of the coil, as well as upon the scale, it cannot be considered entirely satisfactory.

Periodic pressure tests are made on all cooling coils without removing them from the transformers, and very often without taking voltage off the transformer. This we do by disconnecting both ends of the coil and allowing the water in the lower turns to either drain off; or, if both ends of the coil come up over the case, a small rubber hose is inserted on the riser side of the coil and the water syphoned out. To know that the coil is thoroughly dry, and that in the event of its breaking down under pressure, no water will get into the transformer winding, a light blast of air is passed through the coil, which, with the heat from the oil on the outside of the coil, will in a very short time remove any moisture which might remain. One end of the coil is then plugged and air pressure applied by means of an ordinary automobile tire pump. A small pressure gauge connected to the coil shows the pressure on the coil, and also whether or not there are any leaks which would allow the pressure to drop. Generally where there is no back pressure on the coils, 15 to 25 pounds will be as high a test as is necessary.

SWITCHES

Outside of the lightning arrester or line discharger for taking care of high voltages, high-tension switches were probably slower to develop than any other piece of apparatus used in connection with long transmission lines. It is only during the past few years that there have been any high-tension switches on the market, but there are now a number of different designs, all of which have proved generally satisfactory.

The system of the Pacific Gas & Electric Co., was one of the first to use oil switches for voltages in excess of 40,000. As early as 1900 we built and put into operation, switches which were of practically the same type that we are now using. While the switch was in the experimental stages, the frame work supporting the tanks were of wood, and the tanks themselves were the ordinary fibre or paper mache tubs such as are used for laundry purposes. Switches of this kind served their purpose well, and are even now in use after years of service, but where they are called upon to break heavy loads, such as come on at times of short circuit, they are apt to throw the oil out of the container when operated.

To overcome this trouble, we designed a four-break switch, along practically the same lines, but with a considerably greater depth of oil over the contacts. Four-break switches similar to the one shown in Figs. 1 and 2, have been in service in some of our largest power houses for several years, and they have never failed to open the line under all conditions of short circuit.

The particular features which recommend this switch are:

1. The absence of any insulating material that might become saturated with oil and catch fire either from leakage or from an arc.

2. The insulation of the switch from the ground, thereby affording the greatest protection against break-downs due to surges or other high-voltage disturbances when the switch is open.

3. A constant depth of oil over the contacts at all positions of the blades.

4. The comparatively small amount of space taken up by the switch.

We have never attempted to operate any of these high-tension switches either automatically or by any electric or pneumatic means, preferring rather to keep to the more positive hand-lever control. This control has generally proven quite satisfactory, but we have just installed some reverse current relays to be used in connection with the automatic operation of switches on lines which are tied together at both ends. We have yet to learn to just what extent these can be successfully employed, on account of the inherent weakness of alternating-current reverse-current relays, whose operation is dependent on both current and voltage, and the fact that in cases of severe trouble the voltage may drop so low that the relay will be inoperative.

Lightning Arresters

Except in the higher mountain districts the Pacific coast is comparatively free from lightning, and we make no attempt whatever to protect against lightning disturbances.

On most of the early installations, lightning arrester apparatus, such as was on the market at the time, was installed at different points along the line. Practically every type of multigap arrester was tried, all of which proved to be a menace rather than a protection on account of their arcing over whenever there was a heavy line disturbance. The result has been that long since they have been abandoned, and we now use only the horn-gap type arresters with the air-gap set so that they will arc

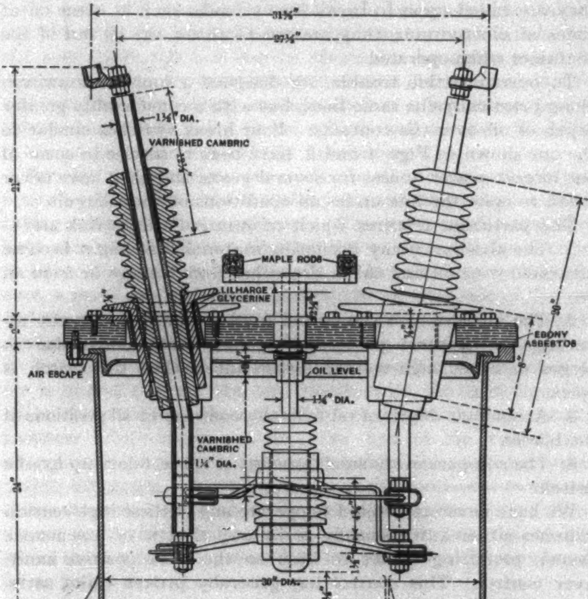
31⅛"
27½"
1⅛" DIA.
VARNISHED CAMBRIC
12½"
MAPLE RODS
LITHARGE & GLYCERINE
EBONY ASBESTOS
AIR ESCAPE
OIL LEVEL
1¾" DIA.
VARNISHED CAMBRIC
1¼" DIA.
21"
2"
24"
20"
6"
30" DIA.
¾" GAS PIPE TAP
SECTION ON A-B

FIG. 1—Elevation of high-tension switch

across on voltages approximately 25 per cent above normal. The particular design of arrester used, consists of two gaps in series with the ground side, connected directly to earth without resistance.

These are used more on account of their being voltage limiting devices than on account of their being a protection against high voltages. Discharges over these arresters always cause a drop in voltage, and very often a momentary interruption to service until the arc breaks. We do not install them at every station, but only at the power houses and more important stations where heavy switching is done. The electrolytic arrester now on the market has been installed on some of the lines in this state but as they have been in service only a short time, little can as yet be said concerning their efficiency or effectiveness.

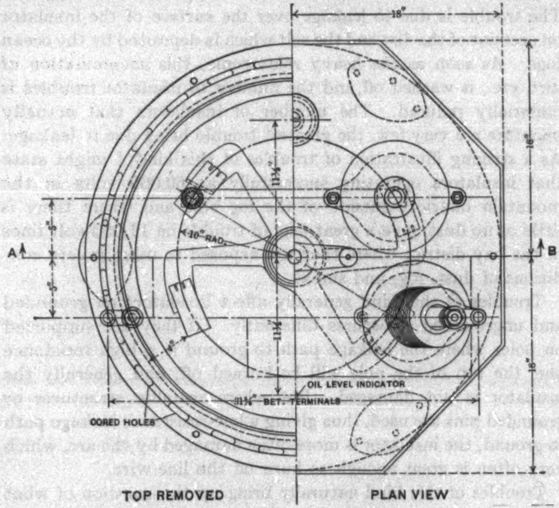

Fig. 2—Plan of high-tension switch

Insulators

The question of line insulation for the high voltages now being used on transmission lines, is the most serious problem engineers have to face, and while it is true that both the design and quality of the insulators manufactured to-day are far superior to those of a few years ago, it is also true that the limiting voltage of a transmission system is governed by the insulators.

The climatic conditions of the greater part of the Pacific coast are peculiar in that there are two seasons, one wet and one dry; and it may seem strange to say that the insulator trouble during the dry season, or just when the first rains start in, is as much as or more than there is during the winter storms. The trouble is due to leakage over the surface of the insulator on account of the dirt and the salt which is deposited by the ocean fogs. As soon as the heavy rains come, this accumulation of dirt, etc., is washed off, and the number of insulator troubles is materially reduced. The number of insulators that actually puncture are very few, the greatest trouble being due to leakage. As a striking illustration of troubles of this kind, I might state that insulators operating successfully at 60,000 volts in the mountain districts outside of the fog belt, and where there is little or no dust, give a great deal of trouble on 11,000-volt lines in the bay district where they are exposed to more severe conditions of dust, fog, and smoke.

Troubles of this kind generally affect insulators on grounded and ungrounded structures differently. If they are supported on poles where the leakage path to ground is a high resistance one, the top of the pole will be burned off, and generally the insulator is not damaged. But where metallic structures or grounded pins are used, thus giving a low-resistance leakage path to ground, the insulator is more often damaged by the arc, which very often is great enough to burn off the line wire.

Troubles of this kind naturally bring up the question of what design of insulator will best meet the conditions, and whether or not the theory that as much of the insulator as possible should be kept dry is a correct one. This theory has been carried out in the vertical or pin type insulator with the result that in the three- and four-part insulators a good portion of the inner petticoat is protected from the rain and cannot be washed by the elements. It therefore becomes necessary to shut down the line and wipe them by hand. This cleaning is especially necessary in the fog district near the bay and along the coast, where it has to be done about twice each year. The suspension insulator has a decided advantage in this respect, in that a much greater part of the surface of the insulator is exposed to the rain and dirt, and is washed off during stormy weather. However, with the higher voltages at which this type of insulator is designed to be operated, there is every reason to think that similar troubles will be experienced, and doubtless the same homely means will sooner or later be resorted to in order to overcome it.

DISCUSSION ON "THE DEVELOPED HIGH TENSION NET WORK OF A GENERAL POWER SYSTEM", SAN FRANCISCO, CAL., MAY 5, 1910.

Markham Cheever: One of the most serious problems that to-day confronts the engineer of an extensive transmission system is the automatic disconnection of disabled lines and apparatus. As the author points out, the fullest utilization of station capacities and the best general regulation of voltage can only be obtained by operating the whole system in parallel. However, the occurrence of anything abnormal at any one point causes a disturbance over the whole system.

Most of the large transmission systems have been a matter of gradual growth, the extensions being made to meet particular requirements, rather than to conform to a comprehensive scheme. It is thus that complicated net-works have arisen, making extremely difficult the satisfactory application of automatic switches. The general experience with automatic switches installed to cut out only the disabled section of transmission line has been unsatisfactory, but it is gratifying to note that relays have been designed to meet the conditions found in one large eastern transmission system and appear to be operating with success. The effort toward maintaining continuous service involves a thorough consideration of the arrangement of trunk lines and feeders, as well as the development of relays that will perform their function properly.

A Member: There is one point on which I would like to ask for information from the eastern engineers and that is the extent to which automatic disconnection devices are used on high tension lines or connecting on to sub-lines or sections of the main line in cases of trouble. I would like to know the class of device that is used for that purpose, and whether it is operated simply by means of relays, operating trips and compressed springs, or whether a small storage battery is used for operating solenoid controlled switches.

President Stillwell: The first instance that I know of, in which the problem of cutting out automatically at both ends a short-circuited feeder was seriously attempted, was in connection with the underground cable system of the Interborough Rapid Transit Company in New York. In that system the Manhattan Power House and the 59th St. Power House are tied together by eight triple cables No. 4/0 B. & S. gauge, and as each station contains nine alternators capable of developing 7500 kilowatts each, and about three times normal current on short circuit, the conditions imposed by short circuit in the cable system are extremely severe. During the development of plans for the Manhattan, the fact that without some such device a cable failure at practically any point might tie up the entire overhead transportation system of New York was realized and discussed, and some of our leading engineers took the position that the possibilities of trouble were such that the use of a high-potential system of distribution from power house to substations was not justified. It was suggested as an alternative that the power be supplied from a number of independent direct current systems.

The automatic circuit breakers first tried were not satisfactory. They were of the type in which one element is connected across the line through a transformer. They generally failed to work for the reason that a heavy short circuit dropped the voltage to a point where they became inoperative.

In the case of the Manhattan substations each is supplied through at least three cables and in most cases five are used. This permits the use of an actuating device for the circuit breakers which depends not upon potential, but upon difference of current flowing in the short circuited feeder and in the other feeders which supply the substations.

Devices of this kind have proved very satisfactory, and now a short circuit in a feeder cable very rarely, if ever, causes trouble in power house or substation. The automatic circuit breakers operate effectively to disconnect the feeder at both power house and substation.

When I became connected with the Niagara Falls Power Co. in 1907, I found in operation a service to Buffalo, supplied through transformers, which increased the dynamo potential from 2200 to 11,000 volts. There were metallic devices at the 2200 volt terminals of the transformers, and also at their 11000 volt terminals. In Buffalo the step-down transformers were similarly equipped, and a short circuit in Buffalo usually blew all four sets of fuses.

The first step that we took in the direction of remedying this was to devise the time-limit circuit breaker, which is now extensively used in power house work. Andrews at Hastings, England, prior to this time, had devised and used the reverse-current circuit breakers, but we did not attempt the use of these at Buffalo.

I see no reason to doubt that it is possible to equip such high-potential networks as you have here in California with automatic overload and reverse current circuit breakers, which will be effective in reducing largely the interruptions of service due to short circuits on the line. In the Carolinas, the Southern Power Co. now has some eight hundred miles of interconnected overhead circuits and have experienced considerable trouble from lightning. The engineers of the company are beginning, as Mr. Downing is here, to make experimental trials looking to improvement by means of automatic circuit breakers. It is good economy to spend even very considerable amounts of money to avoid interruptions of service. They hurt the business and limit materially the rapidity with which the transmission of electric power is being developed in competition with power locally generated.

I should like to ask Mr. Downing a question which relates to the matter of frequency. Some ten or twelve years ago Professor Perrine, then consulting engineer to the company which installed, as I understand, the first plant of the many which now constitute the system of the Pacific Gas & Electric Co., called upon me at Niagara and invited suggestions regarding frequency. I advised him to adopt 25 cycles as being better adapted than 60 cycles to transmission over great distances, pointing out that such systems always grow far beyond the original scope contemplated, and that with the increase in length of circuit, difficulties due to impedance drop would become very weighty. Those installing the plant to which I refer ultimately decided to use 60 cycles, and I should like to ask Mr. Downing, whether, from his present experience, which has covered so wide a range, he would choose 60 cycles if he were to take this matter up *de novo*, or whether he would use a lower frequency. I should also like to ask him about interruptions of service. Any information Mr. Downing may see fit to give relative to these subjects, I am sure would be highly interesting and useful.

L. R. Jorgensen: With eleven different hydroelectric stations to feed into a common network, the continuity of service depends more upon the character of the network than it does upon the character of the power stations. Generally the hydraulic conduit is the weakest link in power generation and transmission, but not so in this case where we have many plants delivering power into the same system. In case of electrical trouble on the system the affected portion is cut out so as not to disturb other portions of the network. If this selection of the affected portion can be done automatically, it is the quickest and easiest way. The larger the system of transmission lines, the more difficult it is to lay out a system of automatic overload switching that will work satisfactorily. In any system, however, it can only be of advantage to have the incoming feeders to substations provided with inverse time-limit overload relays. These relays will work exactly as intended, if the whole substation load can be taken from one feeder at the time, or, if not, the different feeders should feed separate bus bars or separate sections of bus bars. In case, however, the different feeders and bus bars must be paralleled in the substation, the inverse time-limit overload relay would not work at all times as intended, and the reverse-current relay should be substituted. But, if the installation can be made to suit the former relay, it is the best, as the reverse-current relay has not reached the end of its development. The inverse time-limit relay, however, is entirely reliable. Whether the outgoing feeders from the generating station, feeding a complicated network, should be provided with automatic overload relays is a question that perhaps must be answered in each case by trial to find out if the automatic feature does more good than harm.

E. F. Scattergood: There are three or more points which I would like to speak of in a suggestive way. Mr. Downing spoke of the pin type insulator. It has been demonstrated to the satisfaction of engineers in Southern California, at least two or three of them to my knowledge, that on 16,000-volt circuits, affected by fog, the seven-inch two-part mushroom type insulator gives much better satisfaction; that is, the insulator that is spread out flat gives much better satisfaction than the two-part insulator of the same character but with a top section drooping umbrella-shaped. That seems to be demonstrated without question and would simply follow out Mr. Downing's idea of a more open insulator.

The second point is in regard to oil switches. To my mind it is demonstrated quite clearly, that high-tension oil switches should contain a considerable amount of oil; that is, a large cross section of oil on a level with the point of break and a considerable depth above, as indicated by the paper, and that the break should be horizontal; under these conditions the moving terminal is traveling in fresh cool oil if there is any heat at all generated, and at the same time in case there is a partial breakdown on the part of the switch, that is, the formation of gas in the oil at the break, the gas tends to lift, but as there is a large cross section on a level with the break there will be quantities of fresh cool oil banked around on all sides, ready to flow in. So that we have both terminals at all times flooded with fresh cool oil.

The third point is in regard to the telephone system mentioned in the paper. I think you are all acquainted with the two opposite ideas expressed by engineers on the amount of insulation that should be placed on a telephone line in conjunction with high-tension lines. I have heard it stated that one should not use larger than pony glass insulators, in order that there may be leakage of charges which would affect the telephone line. I have heard it stated by well-known engineers that such has been demonstrated. On the other hand it is stated by engineers that there should be strong insulation of telephone lines to avoid their being charged from the high tension lines, especially if on the same poles; and that on a wooden pole line, for example, if the high tension crossarms are put on with lag screws in the center of the pole, and the telephone arm is put on in the same way, using pony glass for insulation, the telephone line will be noisy on account of the lack of insulation.

I want to speak of an instance from which engineers present may draw their own conclusions, because it is not absolutely definite. In connection with the Los Angeles aqueduct we have a telephone line of 250 miles in length, built on separate poles. Notwithstanding the fact that it parallels 33,000-volt power lines, built for Aqueduct construction, along 200 miles of its length. It was built on separate poles and run underground, through well grounded iron pipe, wherever crossing high-tension lines in order to insure perfect safety in its use by all classes of men engaged in the aqueduct construction. Standard D.P.D.G. glass insulators were used and the indoor wiring at telephone stations was carefully installed on porcelain knobs. My idea was that the line should be well insulated, and when it was completed it was what might be termed absolutely quiet, though paralleled by one 170-mile and one 30-mile 33,000-volt line with grounded neutral and a third power line similarly grounded, of between 50,000 and 60,000 volts, for about 20 miles. An additional point is that one and one-half years after its installation, apparently due to deterioration of the insulation, the line gave considerable trouble from noise.

The fourth point I want to put more in the form of a question. The author of the paper, Mr. Downing, speaks of having no trouble in paralleling these different stations, which were built without expectation of their being paralleled. I understand that he means that there is practically no trouble in operation. I would like to ask if he has made any readings or tests to ascertain how much power is being lost in the connecting lines, due to the current necessary for keeping the stations in parallel, aside from the current which would exist there, due to the load. I know of one instance which has since been corrected, but which existed for a while in Southern California, in which a 1500-kw. unit at a considerable distance, tended to hunt a little and sometimes more, and in several instances, when it was carrying as much as 900-kw., it was pulled off the line without the other stations experiencing increase in load. I might say that the hunting in those instances was not sufficient to disturb the system for good operation and good service, yet was bad enough to lose the whole output of that generator up to 900 kw., in a distance of some 40 miles.

W. F. Wells: The conditions in the east are somewhat different from those of the west, and yet you may be interested with a few of the various details. The company with which the speaker is connected operates two generating stations, having a total capacity of 48,000 kw. The current is generated at 6600 volts, 25 cycles, and the transmission lines are all underground. These voltages may seem low even when it is considered that the entire distribution system is underground. These two stations are operated in multiple and all of the substations, about twenty, are connected to the one 6000-volt network. The general method of handling the current is similar to that described in the paper, and which has been used for the past eight or ten years. In order to prevent accidents a very strict code of rules has been prepared and each employe operating in a generating plant or substation, receives one of these rule books, for which he has to sign a slip stating that he has received and read the same. There had been some cases where an employe claimed that he did not know a certain rule was in force, and the court decision in case of accident was adverse to the company. For that reason, both the company with which I am connected, and others in Chicago and New York, have issued these rule books, which are very simple, and which give the general rules pertaining to operation, so that each employe knows how far he may go in any matter. Reliability is the most important thing as shown by one instance. The company has a contract with the City of New York, in which there is a penalty of $500 per minute for interruptions of service, in case current is desired. The transformers used are all of the air-cooled type, no water or oil cooled ones being used. In regard to the switches for these voltages, we have had the same trouble you have experienced on your high tension switches. The present type manufactured by the two large companies operate satisfactorily up to a capacity of say, 40,000 to 50,000 kw., but where the station capacity goes beyond that, and in the case of a short-circuit near to a station, the results are liable to be disastrous.

Reverse-current relays in the cable system are always operative as there is a storage battery in practically each and every one of the substations, thereby insuring a sufficient supply of low-tension current at all times. It is stated in the paper that the horn type arresters are set for a voltage of 25 per cent above the normal. It has been found on our system that voltage surges frequently approximate 100 per cent beyond normal. That probably is due to the greater capacity of the eastern underground cable as compared with the western aerial lines.

John Harisberger: I would like to ask Mr. Downing what experience he has had in opening the switches on the transmission line. The present practice is to cement pins in to the insulator. It would be a splendid idea to use an iron pin in the insulator. I have found that very satisfactory.

P. M. Downing: There is a question in regard to cementing the iron pin to the insulator. In the Puget Sound district, we have practically abandoned that practice by using a threaded iron pin for 60,000 volt service, and have found it very satisfactory.

A. M. Hunt: There is one minor incident in operating transformers that has come to my attention which I thought I would mention. It might be of value to some of you in operating work.

At a substation of the Pacific Gas & Electric Company located at a prominent manufacturing extablishment, there were located three 100-kw., 60,000-volt transformers. It was found that one of the water cooling coils was leaking slightly. It was a very serious matter to shut down the plant. After thinking the matter over, I rigged up a syphon so that the coil could be kept under minus pressure, and it was operated that way for twenty-four hours in order to keep the plant going. Of course, in such a case the leakage would be from the oil side to the water side, and if serious would reduce the oil level, but in this case the leakage was not sufficient to be serious.

A. O. Austin: The extremely variable conditions effecting line insulation on this system have been pointed out by Mr. Downing, and it is in regard to insulators for these conditions that I would like to say a few words.

It was in connection with insulators for these lines that the writer started experimental work which resulted in the development of the high efficiency disk suspension insulators, which have been installed on the largest lines during the past year. Most of the insulators on this system, in addition to having a large percentage of the surface protected, have large variations in diameter throughout the leakage path, and in addition, have the surfaces of highest resistance, limited by small striking distances. This, with a high electrostatic stress on the small shells is the cause of the great depreciation in insulation as the insulator becomes coated with dirt.

The present insulators on this system were the best that could be had at the time they were installed; manufacturing conditions, however, have improved rapidly within the last few years, and it is now possible to make high efficiency insulators which do not depreciate to the same extent when coated. With high efficiency insulators, I believe it possible to insulate these lines so that it will not be necessary to clean the insulators. The high efficiency designs are small for the rating, and are so designed that the surfaces are cleaned by the wind and rain to a much greater extent than the low efficiency insulators.

With the high efficiency designs, it is also possible to provide the line with a much larger factor of safety, the suspension insulators permitting of practically any factor of safety as regards line insulation. The suspension insulators in use on the Pacific Coast are of low efficiency type, having some of the faults of the present pin type insulators, and it is to be hoped that high efficiency insulators will be installed under the same conditions, so that comparisons may be made when insulators have assumed a permanent working condition.

C. F. Adams: There are one or two points which I would like to bring up, one is the subject of the oil switch, and Mr. Wells has just described the ordinary results from the over loading of the switch under service conditions. I presume he refers to what is ordinarily known as type H switch. The chief trouble that occurs is that which seems to be due to the compression of gases in the cylinder, which is too small to contain those gases, resulting in an explosion. The particular switch which is illustrated in the paper, is built upon the theory that the necessary thing in an oil switch is a sufficient depth of oil over the arc that results from opening the switch, and also sufficient area for venting the switch. The entire rim around the top of the tank is vented by a series of holes giving a resulting cross section of several square inches through which any gases may escape. In actual practice this theory has worked out far better than the idea of allowing the gases to compress and thus extinguish the arc by pressure of oil.

There is another feature in Mr. Downing's address on which I had hoped to hear from the manufacturers. There are two types of construction of high-tension transformers. The original high-tension transformers were constructed on the theory that the potential between the high- and low-voltage windings was a possible source of danger; in other words that a break down in the high-tension windings might be communicated to the low-tension windings resulting in a break down of the distributing system, and for this reason the barriers between windings were made more or less fire proof in their nature—micanite being used a great deal.

That theory has been abandoned, though many cases have been found in which local short circuits in high-tension coils have not extended beyond the limit of the coil, and have not burned through the barriers. In later construction the press board insulator has been used entirely, overlooking this feature of transformer construction, and the barrier simply serves the purpose of directing the flow of oil between the various coils.

Another feature of insulation which he discusses is the water absorbing possibilities of the material. For many years the manufacturers went upon the theory that the oil which would enter the partitions would be sufficient to exclude the possible admission of moisture. This theory has not been borne out by practice, and in fact, it is practically common knowledge that press board thoroughly saturated with oil has a continuous affinity for water that may be in the oil; from my own observation I have found that partitions immersed in oil, after a period of some months, would be found to have this peculiar quality: at the upper end of the partition the insulation might withstand 65 or 70,000 volts, while at the bottom of the partition, the thickness being identically the same, the same partition would break down at from 25 to 30,000 volts, and this insulation feature was practically dependent upon the depth of the immersion in the oil, or the height from the top down.

P. M. Downing: In reply to the several inquiries that have been made, I will endeavor to answer them as well as I can.

The first is by the chairman as to whether or not, if we had it to do over again, we would select the same frequency. I endeavored to bring out in the paper that one of the hardest problems that an engineer had to contend with in the operation of a long distance transmission line was the holding up of the voltage on the end of the line due to the inductive drop. It can be overcome to a very great extent by the use of a lower frequency, and after the experience which we have had, it seems to me that I would seriously consider a lower frequency before adopting the 60 cycle.

As I stated in the paper, practically all of these plants were built with the idea of operating as independent plants, and not with the idea of ever being tied into a net work such as we are operating to-day. It is for that reason that we fixed upon

60 cycles, and there is no question in my mind but that the lower frequency would be better.

The second point brought up by the Chairman is as to what part or portion of the load can be taken up by turbines operating in parallel with the system; referring now to the particular system which we have been discussing, we do not attempt to take up the entire load. The steam plants are located at the more important distributing centers, where the service is of most importance, and we only attempt to pick up that important service, and do not try to handle the entire load.

President Stillwell: Is that picked up automatically, or do you have an interruption of a minute or so until you get started?

P. M. Downing: Ordinarily it is picked up automatically, that is, without interruption to the service other than a drop in the voltage.

In reply to Mr. Scattergood's inquiry, as to whether or not there was any appreciable amount of power taken to keep the different stations in parallel—that is rather a hard question to reply to, for the reason that it can only be determined by getting all of the load off the line and seeing what was being required. This, of course, is out of the question, and for that reason I do not know. We do know, however, that there is no great amount of wattless current circulating between the different power houses—practically no current whatever through the neutral of the high-tension transformers, such as was discussed this morning in Mr. Rhodes' paper.

Mr. Harisberger brought up the question of the necessity or desirability of insulating the metal tank of the oil switch from the ground.

This practice is the result of experience dating back a number of years to a time when the art of manufacturing satisfactory insulators was in what might be called its infancy.

The porcelain manufacturers were unable to furnish an insulator that could be relied on to stand the break-down strains to ground even on comparatively short lines carrying light loads.

We are to-day able to get a much better grade of porcelain, and in such shape that it is much better adapted to our requirements, but notwithstanding this fact, the duty imposed upon the switch is much greater than formerly, and the necessity of taking every possible precaution in the way of insulating correspondingly increased.

Insulating the tank from the ground gives an additional factor of safety by cutting down the voltage strains on the bushing insulators entering the switch. Nor have we yet heard any good reason why they should be grounded.

It is claimed by some engineers that grounding the switch tanks is desirable on account of safety to persons coming in contact with it. To a certain extent this is true, but I think the instances where men are required or permitted to work around high voltage switches with power on, are so few that it is unwise to sacrifice the efficiency of the switch in order to provide the additional safety, desirable only under what might be considered extreme emergencies.

The particular air switch referred to by Mr. Harrisberger is a horizontal break, pole type switch, consisting of contact jaws mounted on line insulators with a connecting blade rotating in a horizontal plane. The three moving blades are connected together and controlled by a single rotating shaft operated from the ground.

It was designed to be used as a disconnecting switch on small transformer installations, or on branch lines where there is little or no current to be broken. It was never intended that it should handle currents of any magnitude.

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HYDROELECTRIC POWER AS APPLIED TO IRRIGATION

BY JOHN COFFEE HAYS

INTRODUCTION

Among the many uses to which hydroelectric power is being applied, that of electrically pumped water for irrigation is being advocated at present in a great many instances; and while the mere pumping of the water is so simple as to be hardly worthy of discussion, it may be of interest to point out some of the operating conditions encountered in a project formed chiefly for this purpose.

A hydroelectric system to supply power for pumping water for irrigation will usually be required to build up its own market in the territory served, and it is manifestly necessary at the outset to carefully study the territory. Usually some pioneer work by progressive farmers will show what the land is capable of producing, but the greater part of the territory will consist of barren country planted to grain, or used for grazing purposes, with here and there a town. This land is in large holdings, and the first thing to be determined is the amount of sub-division which may be expected, and whether the proper men are in the field to bring this sub-division about. The character of the land, is of course, of primary importance and the percentage of good land should be carefully determined. Irrigated land should have a slight slope for distributing the water and must be reasonably smooth. Hard pan near the surface must be guarded against, as it generally denotes a rather poor quality of soil. The adaptability of the soil for different products and the climate should be considered, yet data on these two points are hard to get and are usually unreliable. Tests and analysis of the soil would seem to be the natural way of determining its adaptability to the different products, but the agriculturist pays very little attention to these analyses, and has apparently a good reason for this, as they are often unreliable.

In the San Joaquin and Sacramento valleys it has been demonstrated that almost any kind of products may be raised on the good lands. Only a small portion of this land has been planted to citrus fruits, but small groves may be found along the entire length of the valley, and it would therefore seem as though it were all adapted to this class of products if water is applied. The best conditions seem to exist, however, where the mountains rise abruptly from the valley, and the level flat land extends up to the foothills, for, where a long stretch or rolling country lies between the plains and the hills, hard pan and bedrocks are generally very much in evidence.

Due to the fact that the oranges in the San Joaquin valley ripen and are marketed a full month earlier than those in the southern part of the state, they bring exceedingly good prices, and the growth of this industry is very rapid. The present citrus districts, as in fact is most of the land in the citrus belt, are above the existing irrigation canals, which in most instances divert all of the water available from the rivers, and are therefore entirely dependent on ground waters for irrigation; and, as the profits from this crop warrant a large expenditure, it is naturally the best market for power for pumping purposes. Aside from citrus fruits, all kinds of high-class products, such as deciduous fruits, berries, vegetables, nuts, vines, and alfalfa are to some extent also irrigated by pumped ground water.

The amount of water required for the irrigation of different products varies to such an extent in the different communities that it is impossible to get any figures which would be at all accurate. The character of the soil is accountable for the difference to a large extent, but the cost of water and the personal equation are accountable to a very much larger extent. There is usually a marked tendency to the over-use of water. The duty of irrigation water in California is believed to average about 2 ft. in depth in addition to the average rainfall.

In the Imperial valley, in 1906, 120,000 acres were irrigated and a total average depth of 2.04 ft. was used, the main crop being grain. In San Diego county on land planted to citrus fruits an average depth of 1.5 ft. was used from 1889 to 1899. Subsequent dry years, it is stated, lead the growers to believe that too much water had been used. Around Los Angeles it is estimated that an average depth of 2.4 ft. is used.

In the Modesto and Tyrlock districts as much as 8 ft. to 10 ft. in depth was used at the start, but in 1908 the depth varied from 1.2 ft. to 3.6 ft. In the Fresno district very little water is applied to the surface of the land at present, the land being sub-irrigated by seepage from the canals.

Comparison of Gravity and Ground Waters

Where gravity waters are available this method of irrigation is usually much cheaper than by ground waters, and will consequently be used in preference. However, the difference in price is not as great as is popularly supposed, and the cost of irrigation in the case of high-class products is really one of the small items in the total expense, and therefore the use of ground waters may show advantages which will easily offset the difference in actual cost. Ground water irrigation has the following advantages all of which are of considerable importance:

First, the duty of water is higher, due to the fact that it is more economically used on account of the cost of pumping, and the water that is not evaporated and absorbed by the products again sinks into the ground to replenish the underground supply and be used over again.

The second advantage is the drainage function, as the over-use of surface water has, in many cases, ruined excellent land by causing the raising of alkali to the surface, and thousands of acres of the finest lands in the large irrigation districts have been waterlogged and ruined by the excessive use of gravity waters.

The third advantage of ground water irrigation is the freedom from weed seeds which are often carried by ditches and canals, and which, if they do not actually ruin the property, greatly increase the cost of cultivation.

The fourth advantage which the pumped water has is its convenience, and the absolute independence of the farmer using it. The matter of taking turns at the water, and having to use it when you do not want to, and not being able to use it when you do want to, or trouble with the man further up the ditch taking all the water in the dry season and flooding you out in the wet season is entirely done away with where ground waters are used.

The writer has found it impossible to obtain any reliable information regarding the cost of gravity water irrigation except from the large irrigation districts, and even this is incomplete.

The large irrigation districts in Central California are not fully developed, and to take care of the lands which are not yet irrigated, but which are paying their portion of the irrigation tax, reservoirs must be built. The drainage of these lands may be counted upon to cost as much or more than the irrigation. In the case of the small ditches practically no record of costs is ever kept. The cost of litigation is another large item which may be charged to practically every ditch and canal system. Taking all these things into consideration, it will be seen that, even where actual cost is concerned, the pumped water may compare very favorably with surface water in cost, and in fact, there are instances where it is actually cheaper.

The only argument aside from the less expense that the writer has heard advanced in favor of the surface water irrigation is the fact that the surface water may be a better quality, it being nearly always soft and pure, while the ground waters are sometimes hard, and in some cases alkaline and injurious to the products. There are, of course, cases where these conditions exist when the use of ground water is out of the question.

Where intensive farming is practiced and the ground waters are entirely depended upon, some concern has been felt as to the sufficiency of the underground supply, and undoubtedly many localities could be found where more water would be withdrawn from the underground basins than is restored by natural process. The Lindsay district is entirely planted to citrus fruits and other high-class products requiring a large amount of water. Every drop of water used for irrigation, domestic and stock purposes is pumped from the ground, and the water level averages a depth of 60 ft. to 70 ft. when pumping. It would seem that the Lindsay section should show a diminution of the ground water supply, if it is to be a serious problem, as it is probably the most disadvantageously situated district in the county in this respect, yet the water after twelve years of heavy pumping is standing as high in the wells as ever. It is also to be noted that the wells are not what might be considered deep, their average being about 150 ft. to 200 ft., and, as the cost of pumping is insignificant when compared either to the profits or to the expense of the grove, it is apparent that much deeper wells may be indulged in if the waters show signs of decreasing, and within certain limits, the deeper the well the more water.

The San Joaquin and Sacramento Valleys are also favorable storage basins for ground waters, as the only outlet is the San

Francisco bay through the narrow straits of Corquinez. The elevation of the Lindsay district two hundred and fifty miles away is about 300 ft., and the ground waters must, therefore, of necessity travel very slowly and be in large quantities.

DEVELOPMENT OF SYSTEM

In determining the policies and the scope of a proposed hydroelectric system for the supply of power for pumped irrigation, it is necessary to determine at the outset the exact territory to be served and the general policies to be followed as regards charges, contracts, extensions, etc., or, in other words, a definite goal must be set, the power company must do everything possible to assist development, and any inhabitant in any section of the territory must be supplied with power whenever it is required. Therefore, the power system simply grows up with the country, and while this growth is taking place (it of necessity must take many years), it must be considered that the power system is in course of construction during the entire period. This is the main feature in which the power project depending entirely upon an irrigation market differs from the project supplying ordinary commercial business in an already well settled community, and this is a difference which is seldom fully understood and the time element not fully provided for.

The initial installation will usually cover various towns and communities, and, if the territory is partially developed, the development will probably be close to the towns. The business available may, therefore, be fairly well concentrated at the start, and consequently profitable as far as it goes, but naturally only a small amount of the ultimate power required will be marketed. The extensions to the system will be made from these towns, and the fact that development of the community always starts near the town and grows outward is a most favorable condition of affairs for a power company. The price of land is always greatest near the towns, and decreases in proportion to the distance from any center, yet the land near the town is the first developed. These towns are built along the railroad, and being the shipping points, the reduced cost of hauling to the railroad to a certain extent offsets the additional cost of the land.

THE HYDROELECTRIC SYSTEM

The character of construction of a system depends entirely on the class of market, and for irrigation a slight discontinuance of service is not serious, therefore a light construction is permissible. The generating stations at the outset should be of a fairly permanent character, but the distributing system may and actually should be of a light and in many cases even bordering on a temporary character, as it is necessary to economize in every way at the outset to warrant the low rate which it is necessary to charge in order that the market may be developed; for it is necessary at the outset to establish a rate which will continue in effect when the system is fully developed. Even the expense of the generating stations may be reduced to a considerable extent at first, and as the system increases and the market becomes concentrated, improvements of a more permanent nature may be added.

Notwithstanding this, the writer has heard engineers of standing make the broad statement that there was no excuse for the use of a wooden flume and that a tunnel was the only proper thing; also that certain plants were altogether too flimsy and temporary in their design, and that the wooden pole line was entirely obsolete. When these statements are made, the writer cannot but think that the assertions are prompted by a lack of regard for the first principle of engineering, namely, economy. Every one who has had any experience with the wooden flume knows the many interruptions of service caused by it, yet, if constant service is not absolutely necessary, what possible type of construction can compare with the flume. It is short lived, but several can be built for the cost of a tunnel, and during the early life of a transmission system every dollar counts. If the system warrants a tunnel, it may be constructed durng the life of the flume to take its place. Of course, if the systems depends entirely upon one power plant, the replacement of the flume is both difficult and expensive, but few existing systems of any importance rely entirely on one plant, and there is usually sufficient capacity available during certain periods of the year to allow for the shutdown of one station. Also an auxiliary steam plant is often cheaper than a tunnel and much more useful.

Wooden pole lines are also perfectly reliable in our California climate and are a very worthy substitute for the steel tower lines in respect to business development, and there is nothing to prevent the construction of the tower line when the wooden pole has outlived its usefulness; no interruption of service is necessary, as the right of way should be wide enough to accommodate both lines.

Among the different parts of the system where considerable expense may be saved is the switching gear, which may be extremely simple at the outset and still ample. A small galvanized iron building on a wood frame is a thoroughly satisfactory building for the pioneer substation, which can be replaced by a permanent and fireproof structure when the business warrants. By the construction of light, inexpensive tie lines one substation may be arranged to temporarily supply the territory of another, and by the construction of a ring system many miles of expensive transmission line may be replaced by a much lighter class of construction, which will answer all purposes for many years.

In the greater part of California the conditions are ideal for long pole spacing. High winds seldom occur and sleet is unheard of, but it is not uncommon to see a line consisting of three wires ranging in size from No. 2 to No. 8 supported by poles spaced from 120 ft. to 150 ft. apart. However, on new lines, the fallacy of this mode of construction is apparently being realized, and much of the new work looks different. In one case the writer has seen a pole spacing of over 500 ft. in use on light lines, 40-ft. poles being used, which made a very nice appearing and businesslike line. Due to the less number of poles used, better poles, cross-arms and insulators may be indulged in. Other details may be treated in a similar manner.

Description of Typical System

The writer has been connected for several years with probably the only hydroelectric power project that depends almost entirely on pumped irrigation for a market, approximately 70 per cent of the power generated being used for this purpose, the balance of the power being used for the ordinary commercial purposes in towns and settlements within the territory served, and for the operation of one interurban railway. The entire territory, however, is supported by the agricultural and horticultural products, and, therefore, the system is believed to be almost as nearly an exclusive power pumping system as can be imagined. The actual conditions obtaining on this system should apply closely to conditions which may be expected in other similar projects.

Territory. The territory of the company referred to comprises approximately 1,050 square miles in Tulare and Kern counties, California, being a strip of country about 50 miles long north and south, and 22 miles wide. The only available gravity waters for irrigation are the waters of the Kaweah and Tule Rivers, all of which have been long ago appropriated.

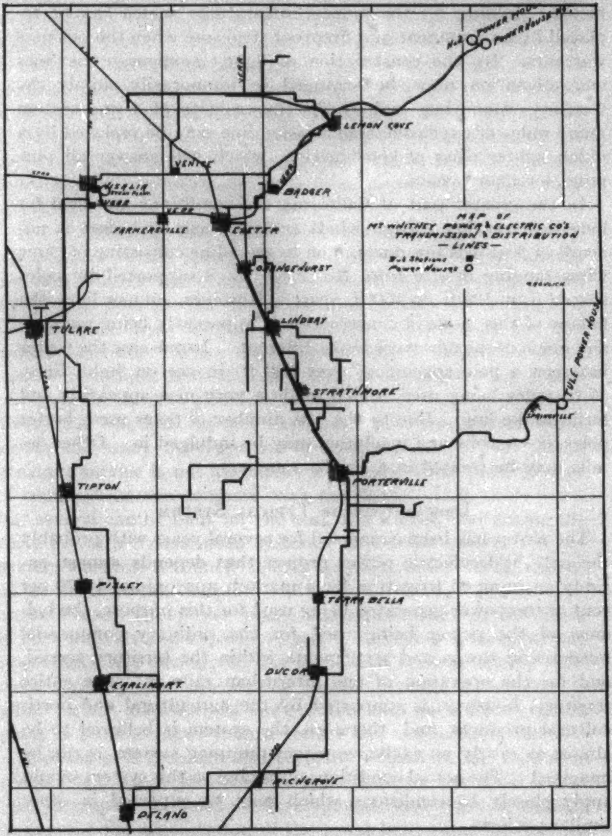
MAP OF
MT. WHITNEY POWER & ELECTRIC CO'S
TRANSMISSION & DISTRIBUTION
— LINES —
Sub Stations ■
Power House ○
No. 2 POWER HOUSE
POWER HOUSE No. 1
LEMON COVE
VENICE
VISALIA
Steam Plant
BADGER
FARMERSVILLE
EXETER
ORANGEHURST
TULARE
LINDSAY
STRATHMORE
TULE POWER HOUSE
SPRINGVILLE
PORTERVILLE
TIPTON
PIXLEY
TERRA BELLA
DUCOR
EARLIMART
RICHGROVE
DELANO

FIG. 1

This gravity water irrigates about 90,000 acres of land and the balance of the territory, or approximately 560,000 acres, must depend entirely on the ground waters for irrigation before they can be made to produce other than grain or pasturage. The average annual rainfall for the territory is about 10 inches, and the soil and climate are admirably adapted for the production of all kinds of high-class products. The territory may be for convenience divided into two sections, the citrus belt comprising approximately 200,000 acres of land, and what may be termed the valley portion. In estimating the power requirements it is considered that approximately half of the land in the citrus belt will be planted to products requiring approximately half as much water as the citrus fruits.

Forms of Contracts and Charges

The bulk of the power is sold under three forms of contract, all being for a period of five years or longer. The contract under which the greatest amount of power is marketed, and which is used by the orange grower, is called the "continuous" rate and provides for the supply of current at the flat rate of $50 per h.p. per year, as measured at the peak load at any time during the season.

The second contract, called the "spring and meter" rate applies to other classes of products, such as deciduous fruits, alfalfa, etc., and provides for the supply of power at a flat rate of $25 per h.p. for the period from February 1 to July 31, when the meter is cut in and all current used during the remaining six months is charged for at the rate of 3c. per kw-hr. The minimum payment during the meter period is $1 per h.p. installed, per month, thereby bringing the minimum charge to approximately $31 per h.p. per year, the flat rate charge being based on the maximum demand. In nearly all cases where this contract is used the annual consumption is not in excess of the minimum. as the total amount of current the consumer is entitled to under the minimum may be used at any time during the meter period. The cost of pumping under this form of contract varies directly with the rainfall, but the minimum will be sufficient for the average season. This contract is used to a considerable extent on land which is irrigated by gravity waters, which are not sufficient in the dry seasons, and is in this way used as an auxiliary or an insurance. This contract may also be applied to the orange growers, and the power required would range from $40 to $65 per horse-power per year, depending on the season. Most consumers, however, prefer the regular flat rate contract, and the " spring and meter " rate is seldom used in this district except in the case of a young grove, where less water is required.

The exclusive use of this form of contract for irrigation would, however, be of advantage to a power company where steam power is used as an auxiliary during the dry season, as the operating ratio would be more uniform under these conditions.

The third long term contract applies to power for miscellaneous commercial purposes not pertaining to irrigation and consists of a meter rate with a graded base rate according to the season of the year. For motors having a capacity of less than 20 h.p. an addition is made to the base rate according to the size of the motor, to motors from 20 to 50 h.p. the base rate applies, and for motors from 50 to 100 h.p. a subtraction is made from the base rate. The minimum payment is $1 per h.p. per month for the rated capacity of the motor. This method of charge, while somewhat complicated, works out very satisfactorily in practice, as will be observed from the fact that practically all other kinds of power have been displaced in the territory. The reason for adopting such a rate will be apparent by a study of the load curve and the curve of stream flow. Naturally most consumers can not regulate their demands for power in such a way as to use the greatest amount during the time of the low rate and economize during the time of the high rate, but the general effect is good and a marked tendency toward the desired results is being obtained.

Aside from the above contracts, lighting rates and a monthly power rate are in force, but include no special features.

Under the pumping contracts, it is to be noted that the same rate is made on any size motor, which is most important, as the sub-division of the land into small tracts is necessary for the success of any community, and the small grower should receive all the encouragement possible.

The above contracts all include the following provisions, which are somewhat out of the ordinary:

1. All contracts are acknowledged before a notary public and recorded.

2. All contracts are an absolute lien on the property of the consumer, the property being accurately described in the contract.

3. The consumer grants the company a right of way over any part of the property described.

The use of the current is limited to the land described in the contract.

5. All delinquent accounts bear interest at the rate of 1 per cent per month, compounded monthly.

6. The minimum charge under the flat rate contracts is for 75 per cent of the rated capacity of the motor.

The advantages of the above provisions are as follows:

No. 1 is explained by those following.

No. 2 protects the company against all bad debts and takes the place of the often-used meter deposit. In connection with No. 5 it allows the company to carry the account of some hard pressed consumer longer than might be otherwise done, as the security, is amply sufficient. There are also many cases where the consumer prefers to pay the interest charge, if he can allow his account to run until the returns from his crops are received.

The third clause is one over which considerable trouble was experienced at first, but is nevertheless the most important one to the company, for, in a country where roads are few and far between, it is continually necessary to cross over private property, and the right of way over the property of one consumer allows for the construction of lines to serve his neighbor. The objections raised to this clause were that the company would have a right to run lines all over the consumer's property and might run right through his front yard or over his house, if it wished, but these objections gradually died out, for the company in all cases takes the path of least resistance, the consumer being consulted where it is necessary to run over his land, and the lines are constructed in accordance with his wishes, even though this is not always the shortest way across. It is also the aim to run all transmission lines on section lines, for it is considered that there should be a county road around each section and that eventually there will be. The company has a franchise over all county roads and naturally uses them wherever possible. The land owners have, therefore, been shown that the right of way privilege has not been abused, and that in all cases where their land has been crossed it has been for the benefit of their neighbors.

Nos. 4 and 5 are self explanatory.

No. 6 is incorporated to encourage the use of the proper size motor for the service required. An electric motor operated at full load feels dangerously hot to the layman, and it is apparently the natural tendency of the farmer to purchase a larger size motor than is needed. The determination of the proper size motor is a simple matter, and a partially loaded induction motor has a power factor that does not do a transmission system any good, so the 75 per cent of the rated capacity minimum payment is rigidly enforced.

By the installation of a double throw switch, the flat rate consumer is allowed the use of current for lighting purposes when not using the motor, ten 16-c.p. lamps being allowed for each horse power contracted for; but, of course, this lighting is confined to the residence of the consumer. The grower generally provides a motor of one or two h.p. capacity for pumping water for domestic use, the pump operating in the day time and the lights at night. Lighting is the only use of current allowed under these conditions, although small household appliances, such as a fan motor, flat iron, vacuum cleaner, etc., may be used. Electric heating and cooking, however, are not allowed, the regular meter rate being used for this purpose.

LOAD CHARACTERISTICS AND POWER REQUIRED FOR PUMPING

The load curve, Fig. 3, together with the connected load, Fig. 2, will show better than any individual examples the amount of power which is required for a large territory with varying water levels ranging from a few feet to 90 ft., and with lifts above the surface at the wells varying from two or three feet to several hundred feet, there being approximately 18,000 acres of land under pumped irrigation at present.

It is estimated that one horse power used in the ordinary way during the respective irrigation seasons will irrigate an average of five acres of citrus fruits and 10 acres of other products in the citrus belt, and 16 acres of deciduous fruits, alfalfa, etc., in the valley section.

The following table was compiled from observation at typical pumping plants on the system. In the table the letters at the head of the columns signify as follows:

A. No. of acres of oranges.
B. Average age of orange grove.
C. No. of acres of vines.
D. No. of acres of alfalfa.
E. Horse power capacity of motor.
F. Horse power tested.
G. Depth of water during pumping season.
H. Height water is raised above surface of ground at well.
I. Total head.
J. Acres per installed horse power.
K. Estimated depth of water available over land if operated continuously during pumping period based on 50 per cent plant efficiency.

Plant	A	B	C	D	E	F	G	H	I	J	K
1	30	3	—	—	5	5	86	4	90	6	2.9
2	40	3	—	—	5	3.0	66	4	70	8	1.8
3	54	15	—	—	12	12.1	50	5	55	4.5	6.3
4	50	3	—	—	7.5	5.2	45	5	50	6.7	4.2
5	16	13	—	—	5	4.7	87	3	90	3.2	5.1
6	20	13	—	—	5	4.5	65	5	70	4.0	5.7
7	22	12	—	—	5	4.7	65	5	70	4.4	5.1
8	10	10	—	—	2	2.4	66	4	70	5.0	4.5
9	48	11	—	—	10	9.1	70	5	75	4.8	4.4
10	40	5	—	—	5	4.6	—	—	80	8.0	2.3
11	33	3	—	—	15	12.9	30	100	130	2.2	6.2
12	16	7.5	—	—	10	10	20	100	120	1.6	8.2
13	110	2	—	—	27.5	27.6	40	5	45	4.0	8.8
14	70	3	—	—	15	15	80	—	80	4.6	4.2
15	35	6	—	—	10	7.8	40	—	40	3.5	8.8
16	135	5	100	—	85	69	20	80	100	2.7	4.6
17	66	3	—	—	10	9.7	40	—	40	6.6	5.8
18	111	2	—	—	15	15.8	27	5	32	7.4	7.1
19	140	7	—	—	50	50	60	90	150	2.8	3.6
20	145	7	—	—	50	32.8	60	87	147	2.9	2.4
21	—	—	30	—	15	12.8	28	2	30	2.0	18.8
22	120	10	80	—	47.5	40.1	50	—	50	4.2	6.3
23	—	—	74	—	15	16.2	35	5	40	5	7.2
24	—	—	—	240	10	7.0	0	8	8	24	3.9
25	—	—	—	160	5	5.6	0	16	16	32	3.5
26	—	—	—	260	15	19.2	16	5	21	17.2	5.5

The above table might be extended and averaged to show the horse power and water required for the supply of various products and for the requirements of orange groves of different ages, but there are so many variable elements entering into each case that any such figures, even if based on an average of every plant on the system, would be, in the writer's opinion, practically worthless. In the case of the high lift plants water is usually taken from the main pipe at different levels, but, as the current is charged for at the maximum demand rate and as the pumps are designed for the highest head, only the high head is taken into consideration.

Fig. 2 shows the increase of connected load on the system from 1903 to 1909, inclusive, for power and lights. This curve does not show the railroad load, which is 600 kw. and was connected in February, 1908, and operates at a load factor of approximately 30 per cent throughout the year. Of the total connected power load at the end of 1909, there was 3,776.75 h.p. used for the pumping of water, leaving 573.25 h.p. for commerical power purposes. This applies to all motors over ½ h.p., sizes under this being included in lighting.

Fig. 3 shows the average monthly load curve at the generating stations for 1901 to 1909, inclusive. The shaded portion of this curve represents the load on the auxiliary steam plant, made necessary in 1908 by the disabling of one generator in No. 1 power house and an extremely low water period of the rivers; and in 1909 the steam plant floated on the line until the Tule river plant was completed late in the season, the other power stations being fully loaded.

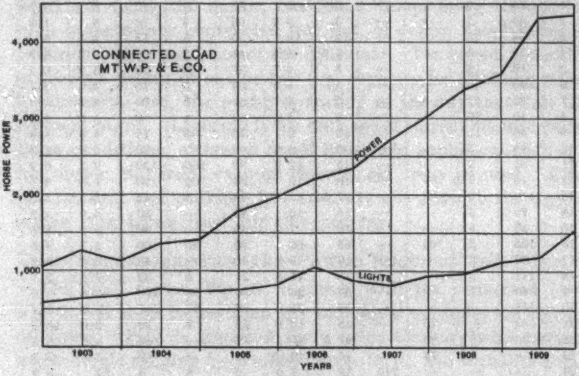

FIG. 2

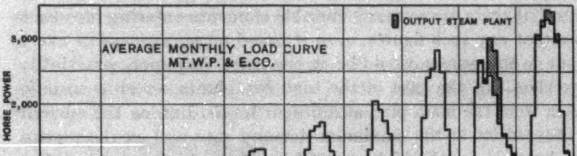

FIG. 3

Fig. 4 shows the load curve for the maximum demand during the years 1907, 1908 and 1909. It will be noted that the maximum demand at the power stations is very much less than the connected load, regardless of transmission losses, although the pumping load is considered extremely steady during the irrigation period, the pumping plants operating 24 hours per day at as near the full capacity of the motor as possible. The lighting load has no appreciable effect on the generating stations during the time of maximum demand. as it is balanced by a certain amount of power used only during the daylight hours.

Fig. 5 shows the load factor of the system, and this also clearly points out an important condition to be considered in an enterprise of this character, as it is comparatively low. This curve shows that a large amount of power is available for market during the winter and spring months, and with such market obtainable, the capacity of the generating stations could be greatly increased, as the flow of the rivers is greatest at this time.

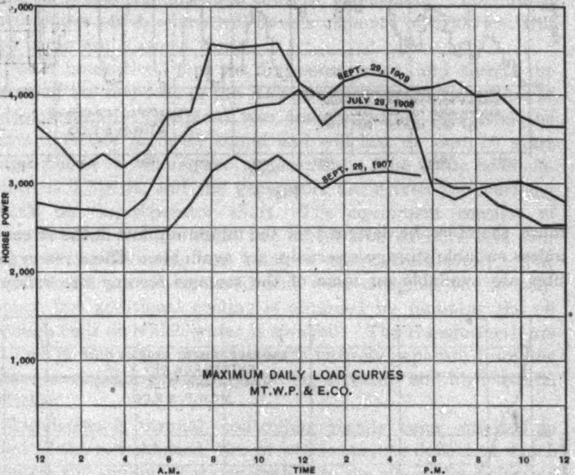

Fig. 4

Fig. 6 shows the characteristic flow of the streams during a very dry season, and is a combined curve of the Tule and Kaweah rivers. All of the rivers flowing into the San Joaquin valley have the same general characteristics, and a comparison of the load curve and this curve of stream flow shows the time of heavy load during the period of low water, and the generating plant must, therefore, be designed for the minimum flow of the stream unless suitable storage reservoirs are available. These reservoir sites are available on some of the streams feeding the valley, but in the case in point are scarce and expensive to develop, and the plants are designed for the minimum flow.

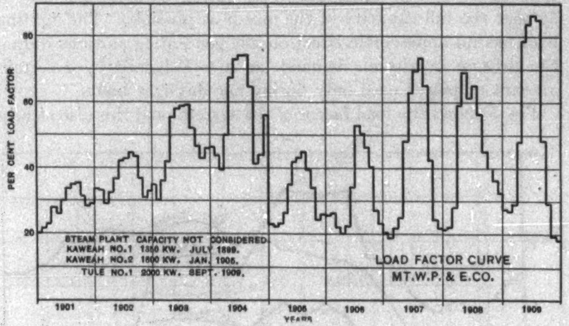

Fig. 5

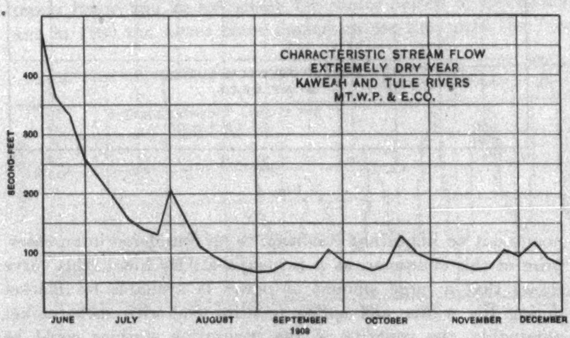

Fig. 6

In connection with the load factor curve, it is to be noted that when the load factor reaches approximately 50 per cent it is necessary to construct an additional plant.

GENERATING STATIONS

The generating stations consist at the present time of three hydroelectric power plants having an aggregate capacity of 4,850 kw. and one turbo-generator steam auxiliary plant having a capacity of 1,000 kw. Two of the water-power plants are on the Kaweah river and one on the Tule river, the steam auxiliary being in Visalia, the principal town on the system. The fourth water power plant, which will have a capacity of 3,000 kw. will also be on the Kaweah river.

Power house No. 1 was the first constructed, and diverts the waters of the east fork of the Kaweah river through six miles of redwood flume. The plant was constructed in 1899, and the flume is to-day perfectly sound and will last at least 10 years longer before it will require replacement. The static head obtained is 1,310 ft. and the generators are driven by overhung wheels on the generator shaft. The equipment consists of three units of 450 kw. each, two belt-driven exciters, and four 500-kw. transformers, one being a spare transformer. The transformers are oil-insulated and were designed to be self-cooled, but additional cooling is obtained by pumping the oil through coils on which water is sprayed. The transformers are located in individual compartments entirely separate from the power house, as are also the lightning arresters and high-tension switches.

Regulation is manual, controlling stands being situated in front of the switchboard, two of which operate deflectors which regulate the amount of water applied to the wheels by deflecting the stream, and one of which regulates the water supply to the third machine by a needle nozzle. At the penstock a regulating reservoir in the form of a large flume has been constructed, having a capacity of 25,000 cu. ft. The main function of this reservoir is to smooth out the daily variation of stream flow, as, due to the method of regulation at the power house, no great economy of water can be practiced, although the needle nozzle allows the regulation of water to some extent. Since the other plants have been constructed, however, no regulation is done at No. 1, which simply takes a certain load and holds it.

Plant No. 2 was constructed during 1904 and put into operation in January, 1905. The water for this plant is diverted from the main Kaweah river, and is conducted to the penstock through 15 flumes aggregating 0.87 mile, and 3.1 miles of ditch. The flumes are all redwood and the ditch is concrete lined, the ditch construction being used where the slopes will permit, the flumes being constructed on the rough broken ground and to cross ravines. A concrete lined penstock reservoir is excavated in the side of the hill having a capacity of 75,000 cu. ft. The static head is 360 ft. and the power house equipment consists of three units of 500 kw. capacity, each direct connected to high-head turbines regulated by Lombard governors. Two turbine-driven exciters are installed, which are hand regulated. Seven 350-kw. step-up transformers are installed in compartments outside of the power house, one being in reserve. The transformers are cooled in the same manner as those at No. 1 by circulating the oil.

The No. 3 Kaweah plant, on which construction is just started, will divert water from the main Kaweah river, which after passing through a conduit 10 miles long, will discharge just above the intake of No. 2, thereby using the water twice. The static head of this plant will be 1,960 ft.

The transformers at Nos. 1 and 2 are arranged on trucks so that they may be easily run into the power house under the crane for repairs, etc., if necessary. In No. 1 individual tracks are run from each transformer, and in No. 2 a transfer truck is run on the track in front of the transformer compartments, so a transformer may be pushed out on to the transfer truck and taken to a short piece of track entering the power house. The switching gear in both stations is arranged so that the spare transformer may be immediately cut in in place of any other transformer.

The buildings at both Nos. 1 and 2 are constructed of corrugated iron on wood frame; foundations, floors and transformer compartments being constructed of concrete. The corrugated iron structure is, for all practical purposes, ample, as the climatic conditions are most favorable, and a protection from rain is about the only requirement necessary. These buildings are, however, cold in winter and hot in summer, and would not be considered strictly permanent or fireproof.

The third, or Tule river plant, was constructed in 1908 and 1909, and started operation in September, 1909. The water is diverted just above the junction of two forks of the river, there being two diverting dams and headworks from which short flumes lead to a point at approximately the junction of the river, and join. The water is conducted to the penstock through

4.5 miles of pine flume, 2.06 miles of concrete lined ditch and 880 ft. of inverted siphon pipe, the siphon working under a 5-ft. head and having its lowest point 120 ft. below the conduit grade. This siphon was used to cross a long gulch.

The ditch is lined with concrete and excavated well into the mountain, very little reliance being placed on the filled bank, the water level being only 6 in. above the natural level of the downhill slope. The ditch is 4½ ft. wide and 3 ft. deep, the sides sloping 1 to 1. It is lined with concrete 2½ in. thick, over which ½ in. of cement plaster is applied. A small amount of alum was mixed with both the concrete and the plaster, which renders the lining practically water tight. Due to the steep slope of the mountain side and the size and depth of the ditch, the sloping of the upper bank to a slope of 1 to 1 required considerable excavation. However, the finished product is a most permanent piece of construction. The flume is of the standard bent and stringer construction, the bents being placed 16 ft. apart, and a strip of burlap saturated with an asphaltum compound is placed under the battens for waterproofing.

At the penstock a regulating reservoir is excavated in the side of the mountain. A small portion of the upper end is 5 ft. deeper than the balance of the reservoir and is used as a sand-trap. The reservoir is 12 ft. deep, 350 ft. long and of an irregular shape, varying from 12 to 125 ft. in width, following the contour of the hill. The side slope is ½ to 1, and it is lined with 8 in. of concrete and ½ in. of plaster. A concrete wall at the end separates it from the penstock.

The reservoir has a capacity of 175,000 cu. ft., which will operate the plant 1¾ hours at normal load. Therefore, in the case of a break in the flume, sufficient time will be available to start the steam auxiliary plant without interruption of service. The reservoir also has sufficient capacity to regulate the daily fluctuation of stream flow during the low water period, so that the highest use may be made of the water. The static head is 1,135 ft., and the whole plant is designed with a view of ultimately doubling the present capacity.

The power house equipment consists of two 1,000-kw. units with overhung wheels, Lombard governors, directly actuating needle nozzles, an auxiliary nozzle being provided which automatically opens in the event of the main needle nozzle closing too quickly and ramming the pressure pipe. These auxiliary nozzles, when opened, close at a predetermined speed regulated by the dashpot principle. This arrangement allows the most economical use of the water. Two exciters, each of sufficient capacity for both generators are installed, one being driven by a water wheel and one by an induction motor. Seven 400-kw. water-cooled transformers are placed in the transformer room on one side of the power house, one transformer being held in reserve. Lightning arresters and high-tension switches are in a separate building.

The power house building and arrangement differ from the other plants in several respects. The power house is constructed of ferroinclave on a steel frame, the ferroinclave being plastered on each side with 1½ in. of cement plaster, therefore making a reinforced concrete roof and sides 3 in. thick. A partition of the same thickness divides the generating room from the transformer room and a similar partition divides the transformer room into two compartments, fireproof doors completing the separation. The switch house is constructed of the same material, and both buildings have metal window casings and wired glass windows, no wood being used in the construction. The above may seem inconsistent after the statement that the other power house structures were practically sufficient, and this would be the case, were it not for the fact that the transformers which present a certain fire hazard are placed in the power house building. Also the company has passed the pioneer period, and can, consequently, afford a little more permanent construction.

The switching gear and wiring has been greatly simplified by connecting the transformers in two banks, the spare one not being connected. The transformer "railway system" is also dispensed with simple rollers being provided instead. In the event of an accident to one transformer its bank may be disconnected, the leads removed from the affected transformer, water pipes disconnected and the transformer skidded to one side. The spare transformer can then be skidded into place and connected up and the entire job performed in about one hour, certainly a short enough time for a system of this character.

In connection with all of the power stations, the question of the operator's comfort has been given proper attention. From a practical business point of view, this is a paying investment, as a much better class of men can be procured. Comfortable cottages are provided, the surrounding grounds are cultivated and a small ice plant is a part of the standard equipment. A few fruit trees and a garden will not only greatly improve the looks of the property, but will also greatly reduce the boarding house expense.

TRANSMISSION SYSTEM

As shown in Fig. 1 the transmission system is in the form of a figure 8 or a double ring. In this way current is available at both sides of any sub-station, thereby giving all of the advantages of duplicate lines. The main transmission line from power houses Nos. 1 and 2 feed in at the northeast corner of the system and the line from the Tule river plant feeds in at the center of the system. The steam auxiliary is in the northern ring and can consequently feed both ways. The old transmission lines have wires spaced 36 in., the sawed redwood poles being spaced 120 ft. apart. The new transmission lines in the valley consist of a double circuit, the 34,000-volt lines being placed on one side of the pole and a 6,600-volt distributing line on the other side. The circuits form equilateral triangles, the apex of which point downward; the wires are spaced 36 in. apart on each circuit. The main line from the Tule river plant consists of one circuit, the poles being of cedar 35 and 40 ft. in height and spaced 300 ft. apart. On all new lines a pole spacing of from 300 to 420 ft. is used, with 35- and 40-ft. poles, depending on the character of the country.

The current is distributed from 12 substations situated in the various towns and settlements, and the transmission and distribution systems are laid out to provide for additional substations as the load increases. The substation construction varies, all but one having started in the same way, namely, as a cheap wood or galvanized iron building with the most simple switching apparatus, and, as the substation grows in importance, substantial brick buildings are constructed with more or less elaborate switching gear, storerooms and offices.

The power is distributed at 6,600 volts and 2,200 volts, two-phase, the first distributing being at 2,200 volts; 6,600 volts eventually proved more satisfactory on the power circuits. The city lighting systems distribute at 2,200 volts, two-phase, with the exception of two new systems, where three-phase has been adopted. There are 246 miles of 6,600-volt line, 53 miles of 2,200-volt line, and 28 miles of lighting circuits of 2,200 volts and about the same length of low-voltage line with a connected load of 1,190 kw. of lighting transformers. The consumer supplies the secondary transformers for power supply and the power is measured on the primary side of these transformers.

EFFECT OF POWER PUMPING ON LAND VALUES

While some exception may be taken to the statement that the development in this section is due almost entirely to the application of electric power for pumping purposes, it is, at the same time, believed to be the case, and this seems to be proved by the land values where pumped irrigation has been established.

Unimproved lands lying south of Porterville sold in 1890 for from $5 to $7.50 per acre, in 1900 for $10 to $15 per acre, and in 1909 for $60 per acre and higher. Lands north and east of Lindsay, which sold in 1895 to 1900 at from $35 to $40 per acre, now sell at $150 per acre. The assessed values of two sections, one three miles north-east and the other one mile west of the town of Lindsay, show that in the first instance the assessed value was $14 per acre in 1890, $36 in 1899 and $91 in 1909, and in the second instance $19 in 1890, $36 in 1899 and $117 in 1909. The above figures represent about the average conditions, there being many cases of increase where the figures have been greatly exceeded.

INVESTMENT VALUE OF A POWER IRRIGATION PROJECT

The application of a hydroelectric system exclusively for the furnishing of power for pumped irrigation from an investment point of view is not of the get-rich-quick variety. The investor who wishes to receive immediate results on his money should not enter into any such scheme, unless the power company owns the lands to be put under irrigation, when the project develops into a real estate transaction, the power part being insignificant. Where the project is confined wholly to a power proposition, it should be gone into only by the most conservative investors or developers and pioneers who are content to bide their time and be satisfied for many years without dividends, but with the increased value of their investment. The power company must indirectly meet the opposition of other irrigation districts, and the large government projects, as well as the opposition of gasoline engines and other power, and the charges for service must be as low as possible.

The territory served is sparsely populated at the start, and usually no irrigation is indulged in except by some few scattering pioneers, who may be using gas or steam engines and windmills, and the marketing of power, therefore, depends entirely on the rate at which the territory served is put under high-class cultivation; and this is a slow process. To support a project of any magnitude requires an immense territory, and in the early years of development it is not unusual to construct a line five or ten miles long to supply a motor of as many horse power; for any part of the territory must be supplied regardless of its location with reference to existing lines, and everything must be done to encourage the development of the entire territory taken as a unit, and, for the first few years, even though the territory is settled rapidly, it can not be hoped to make the power project pay.

The power company after a few years should show a profit above interest charges and operating expenses, but for every dollar earned several more must be expended on extensions, and, while it is true that, after the system commences to show earnings a great many extensions may be taken care of by bonds, these always require a certain amount of money to be provided by the company. If the development is rapid the stockholders are often required to subscribe additional money aside from the earnings, and must in many cases content themselves solely with the increased value of the property. The increased value of the property may be large and the investment, as far as security is concerned, be of the finest, as it usually is; but in this day of progress and quick returns on investments it is rather difficult to find many investors who are content to wait a generation before receiving any actual cash returns on their money, no matter what the company's books may show as to earnings or as to increased value of property.

When the system is fully developed and loaded the dividends may be large, and the reliability and permanence of the market will often place the stock almost on a bond basis, and in this way a carefully planned and developed hydroelectric system for the supply of power for pumped irrigation may be considered a splendid investment, but never in the light of a speculation. It must be clearly outlined at the inception of the enterprise just what is to be accomplished, for it is a long job and one which requires a great deal of looking into the future.

The final results must be arranged for years before they are obtained and everything shaped to this end. A desire to hasten the marketing of the power may set some precedent which would be most difficult to overcome, and the failure to provide for emergencies may undo the work of years and completely demoralize a system. An overloaded system is to be particularly guarded against, as too much valuable produce depends entirely on the service, and any damage to the producer may completely stop development and stifle the entire community. The power company, therefore, has a very large moral responsibility to face, which is not to be lightly considered.

DISCUSSION ON "HYDROELECTRIC POWER AS APPLIED TO IRRIGATION", SAN FRANCISCO, CAL., MAY 6, 1910.

President Stillwell: The possibilities opened up by the application of electric power to pumping water for irrigation in California, are obviously very great. A recent publication by the United States Geological Survey estimates the available water powers of California at 7,000,000 twenty-four hour horse power. Assuming twelve tons of coal per horse power per annum in 24 hour service, that power would require for its production by steam, 84,000,000 tons of coal, which happens to be approximately equal to the anthracite output of the coal mines of Pennsylvania. So vast an output of power, if utilized in manufacturing, would supply a very much larger power market than even California can hope to develop in many years. It is peculiarly interesting that many of these powers exist within practicable reach of land requiring water for irrigation.

A paper which was read at the recent Irrigation Congress at Albuquerque by Mons. Tavernier, Chief Engineer, Department of Public Works, Republic of France, deals with this subject and its conclusions are particularly interesting when considered in the light of similar experience by Mr. Hays and his company. Mons. Tavernier reaches the conclusion that even considered from the standpoint of power economy, it is frequently not more expensive to use water power to operate dynamos, which in turn operate motors lifting water by pumps to the land which requires irrigation, than to distribute water by ditches. According to his figures, the efficiency of the two processes in many cases is practically identical.

E. W. Paul: I would like to ask Mr. Hays in regard to his table given in his paper. I don't quite understand it. He has a plan here of eight and ten acre groves, ten years old, and to irrigate that requires a two h.p. motor. The experience of farmers in the south, with which I am familiar, is that they do not want to irrigate one row of trees at a time, but they want to flood the whole orchard at once. This requires considerable water. I do not think that a two h.p. motor would do that. I would like to ascertain whether they do irrigate the entire ten acres, or do they sit up all night changing the water from one row of trees to the next. I would also like to know if the company with which he is connected requires the motor to be taken off the line on the peak load, and if it does, how they overcome his objection to that feature.

J. C. Hays: The two h.p. motor is correct. Some of them have small reservoirs which will hold the water, and they run that motor continuously 24 hours, and they do irrigate probably ten or twelve rows a day from this little reservoir made of dirt, in some cases, they irrigate a very few rows at a time as they go across their orchard, and they figure that this flat rate will keep them all the time. This dry bog country has to dry out before they can cultivate it. As to taking the motor off on the peak load—as irrigation is the only peak load we have, they work all the time.

F. V. Henshaw: Mr. Hays describes an electric power system which was apparently built entirely on a fore knowledge of there being sufficient underground waters to enable the plant to get its business by pumping for irrigation, and presumably before going into this project, the extent of those waters was very carefully determined. I think it would be interesting to learn from Mr. Hays the extent to which the underground waters of the San Joaquin Valley have been examined, and whether today it is known that there is a sufficient supply there, in all probability, to irrigate all of the land that cannot be covered by surface waters by gravity distribution. Another point occurs to me, regarding the cost of construction; Mr. Hays says: "If constant service is not absolutely necessary, what possible type of construction can compare with the flume?" I take it that the flumes are built very light, and the point is as to how long an interruption the farmer can stand under extreme conditions. We will say an orange grove, which is at a point where it needs the most water—how long can it be without water without serious damage.

J. C. Hays: I do not know the extent of the underground waters in our state. I have read several papers and reports on the subject but believe that the only way we can tell is to pump.

F. V. Henshaw: I thought you had been doing that.

J. C. Hays: Well, we have in some places. But you can hardly call that conclusive. We have been pumping in one district for ten years, and apparently the supply of water is not diminished. So it naturally looks like there is something there. The water shed of the valley is large enough to take care of the underground waters, and the formation of the deltas in these rivers is of such character on the east side that the water percolates very slowly. On the west side, I understand, there is a different condition where the water flows out very fast; consequently, we are liable to find variation in the wells, but there is a very little variation in the wells on the east side.

F. V. Henshaw: Did you find any wells that had a flowing head?

J. C. Hays: Yes, in what I call the valley portion. But artesian wells are not considered very good for irrigation. I personally do not know much about that subject, but I do know that there is sulphur, or something deleterious in the water, and I know of one peach orchard that was killed by it. As to the subject of the flume—I don't know just how long an orange orchard could go without water. They claim in that country that if they do not irrigate for about two weeks in a very hot season, the trees commence to show it. Most of the growers claim that they can look at the trees and tell when they need water.

An interruption on the flume or the line, for instance, would not amount to over 24 or 36 hours, possibly 48 hours, and an interruption of that length would do no damage. Of course, during certain portions of the year, landslides cause some damage, but I do not remember of any landslides occurring during the irrigation season. They always occur in the winter time, and never during the irrigation season.

H. Homberger: The Mount Whitney Power Co.'s system is of particular interest to the hydraulic engineer, being a power system where 80 per cent of the power is generated hydraulically and 70 per cent of the power used for pumping. How entirely different the conditions are from those of the average commercial plant with a mixed load, has been most ably and clearly explained. There were a few points mentioned which I should like to be further enlightened upon.

First, the question of high price permanent construction as compared with low price temporary construction. It was stated that engineers of prominence have broadly condemned the wooden flume and the wooden pole line as compared with the tunnel and steel towers or reinforced concrete poles. Such a stand can only be explained by entire disregard of special conditions; there is no greater danger in engineering than unwarranted generalizing of principles of construction and wrongly applying what is good in one case to some other case where it might not fit in at all. Personally I am not in favor of wood as construction material and would rather see an inorganic material used. To be sure, 20 years is a remarkably long life for a flume, and I think not to stand alone with the statement that half that is nearer the average. Similar are the conditions with a wooden pole line. It seems to me, however that generally too much stress is laid on the difference in first cost and the fact not taken in consideration, that considerable expense is connected with the necessary continuous patrolling and maintenance of such structures, which if capitalized, would go a long ways towards providing for the higher first cost of a more permanent type of construction, which, as stated, will ultimately have to be resorted to anyhow.

A second point: Balancing reservoirs were mentioned at the head of the pipe lines; while the reservoir of the latest plant, the Tule River Plant, has sufficient capacity to operate the plant 1¾ hours under full load, at the Keweah No. 1 station it holds out only 25 minutes and at Keweah No. 2 even less than 19 minutes, which is certainly of little value in case of trouble in the gravity conduit system. The main function of the latter two reservoirs is stated to be, to smooth out the diurnal fluctuations in the steam flow, but even a reduction of 2 per cent in same would empty the reservoir, if the plant is to be kept under full load for 24 hours, which is practically the case during the pumping season, as shown in the daily load curves Fig. 4. Maybe I did not understand this correctly and I should be thankful to have it explained.

Third: With an average load factor of 50 per cent the fixed charges on a hydroelectric plant must be quite high, and with the stated low rates for power it would be interesting to know, whether a large capacity steam plant to be operated during the irrigating season would not make a better financial showing than an additional hydroelectric plant with ten miles of conduit. This might be advantageously located in the Coalinga oil field region, only about 10 miles distant from Visalia, as it might prove more economical to ship current by wire than oil by rail or pipe line.

L. Jorgensen: In general the hydraulic conduit is the weakest link in power transmission for the reason that, from a financial standpoint, it cannot be installed in duplicate. Therefore, on systems with only one or two power plants it is most important to have this link well built. Tunnels are not the only safe conduit, but concrete pipes completely buried are in most cases just as safe, cost only half and require less grade, due to their better hydraulic shape. It is true that a flume costs only about half as much to build as a concrete conduit costs to install, but, if the depreciation, maintenance and interest on the investment are taken into consideration, their cost will be the same. Then the question of whether to use a wooden flume or a concrete conduit is simply a matter of whether the greater amount of money required to cover the first cost of the concrete conduit will balance against the additional safety connected with the use of a buried conduit. How tunnel compares in cost with either wooden flume or concrete conduit will depend upon how much of a short cut it makes. The first cost per linear foot may be four times that of a flume of the same carrying capacity, but a flume or concrete pipe line must follow the contour of the hillside, whereas a tunnel cuts through the hills.

Where the country is flat and otherwise adapted for ditch construction, ditches will be the cheapest, as maintenance cost is lower than for flumes, and depreciation is practically zero. Wooden stave pipes will accomplish the same as concrete pipes and have a lower first cost. If buried they are protected against rolling boulders, frost, etc., but their life is very short and repairs are difficult to make. Taking it all in all the concrete conduit does not seem to be as extensively used as all its good properties should warrant.

E. W. Paul: I would ask Mr. Hays if, on some of these circuits running to pumping plants, he has made any provision on the customers' premises to take care of the motor in case the current goes off the line, that is, as to voltage switches, and also how he even gets farmers to sign the contract described, with the conditions mentioned in his paper?

Ralph W. Pope: I am familiar with the territory where this plant is situated that has been developed for the raising of oranges. I was there twenty years ago when most of it was devoted to the production of wheat. At the time this plant started or a little earlier, the soil had deteriorated owing to continuous wheat cropping. I understand from the author that the soil was exhausted only about four or five inches down, so that orange culture is now pursued with great success. Referring to Mr. Henshaw's inquiries in regard to the pumping, I understand that pumps were formerly operated by windmills or gasolene engines, and that wells had already been dug, so that the question was not whether water could be got there, or not; because it had already been obtained.

There are certain tracts however where the water cannot be reached by digging or boring. The only value pertaining to such land is the possibility of selling it to eastern tenderfeet, which is another source of revenue not mentioned by the author.

In regard to the light construction of this plant, it must be remembered that at the time it was started, while having the water power, something like 7000 h.p., I believe that the question of a market was rather problematical, and ordinarily that is one of the most important questions to be considered in developing a water power plant. It was for this reason that the cheap construction was used in this particular instance. Those of you who are familiar with railroad construction throughout the country, know that in early days the construction was frequently of a very cheap character in comparison with what it is to-day. Railroads at that time were an experiment, but as the importance of proper construction developed, and rebuilding was undertaken it was found advisable to strive for permanency. This paper indicates that it is a long, slow process to develop an enterprise of this kind, but when it is permanently established it becomes an attractive investment, if you can find a territory where these conditions prevail. In Utah, I think they need something of this kind, as they have used up about all the water power that is available in that state.

Markham Cheever: Answering Mr. Pope's inquiry regarding the conditions in Utah, underground waters occur in large quantities in the fertile valleys of Utah Lake and the Jordan River, and artesian wells are numerous. However, this water is not used for irrigation to any great extent.

Utah Lake is one of the largest bodies of fresh water in the West and forms a natural reservoir from which the canals of the Jordan River Valley are supplied. As the lake level lowers during the summer, the outflow is maintained by means of large centrifugal pumps. Several projects involving the pumping of water to land lying at a considerable elevation above the lake are contemplated and one is now in operation. While hydroelectric power is used or proposed for all these pumping propositions, the load is not as satisfactory to the power producer as that of the project described in the paper, on account of the much shorter irrigation season in Utah.

F. V. Henshaw: I would like to add one word, that this matter of underground water is a very essential thing to anybody contemplating going into an enterprise of this kind. I can say positively that in some parts of Colorado, the subject has been very thoroughly investigated and the water is not there. I would like to tell you where, but am afraid it would hurt the feelings of some " eastern capitalists."

A. J. Bowie Jr.: This load curve is different from any others I have seen in that there is no peak in the evening. This is of interest in matters of irrigation, since the value of the power which can be supplied, of course depends on the nature of the load curve and how the power is used. When the peak comes in the evening the power company can afford to supply power very much cheaper to the farmers who will shut down at that time. The load for irrigation differs from other types in that it is possible that suitable arrangements may be made to cut it off for a few hours a day without suffering serious inconvenience. This is particularly true where small reservoirs are used, reference to which has already been made, and the value of these reservoirs I consider of very great importance in the problem of irrigation. These reservoirs should hold about a day's supply for the farmer, who by that means is enabled to employ his water at such hours as are most advantageous. If his pumping station is small, he may use his entire supply in a few hours, instead of having to devote the entire day to the use of water. These reservoirs constructed of earth, are used in a great many parts of the country, and sometimes they are lined when the earth is unsuitable for holding of water. One form lining consists of coal tar, lime, and sand, spread on half an inch in thickness. I have also seen this lining applied, where the reservoirs without it would not be able to hold water.

These reservoirs cut down very materially the size of a plant which it is required to install, as well as the corresponding additional investment and they avoid all night irrigation. The economic consideration of irrigation requires a suitable proportioning of the various items of expense which make up the cost of pumping, which may be segregated as (1) the cost of fuel or power, (2) the attendance and (3) the fixed charges, as well as the cost of applying the irrigation water to the land. The sum of these charges should be reduced to a minimum. In irrigating plants the depreciation is generally high. I think, allowing for all fixed charges, 20 per cent, would often be a low figure to cover interest and depreciation repairs and renewals. It is not unusual in countries where fuel and labor are cheap to find the fixed expenses exceeding the other two expenses. A small reservoir would avoid this and be a considerable saving in this way.

In Southern Texas the average depth of irrigation water used annually was 2.7 feet for all crops, while for alfalfa it was 5.7 feet. The efficiency of most of the pumping plants in that country was exceedingly low. That would apply to any country where plants of a similar type were employed. The cost of pumping an acre foot of water one foot high was four cents, and as the power to raise an acre foot of water one foot high is equal to about one water kw. hour, this would amount to about 4 cents per water kw. hr. This is an average of course.

It may be of interest to you to know that we have quite a little irrigation in the Eastern states for truck gardens. The depth of water employed there depends on the source of supply and the cost of obtaining it, and varies from four to eight inches per year. Many farmers are using city water irrigating to an annual depth of about four inches. This costs for water about $25 per acre per year, where as when pumped water is used, about twice the depth is used at the same cost per acre per year. The average increase in crop values per acre due to irrigation, and allowing for wet and dry years, is about $200 per year over and above all expenses. In other words this is the average net profit of the farmer from irrigating. Of course that is large, but the crops raised per acre are of great value, in some cases going as high as $1500 per acre per annum, so that it does not take very long even in a wet year to make a substantial gain.

W. A. Doble: I think Mr. Hays' excellent paper has been somewhat misunderstood with reference to the cost of this Mt. Whitney plant. We must bear in mind that that was one of the very earliest plants to be built, and was considered at that time the most thorough and best construction that could be done. It was considered that that was the best that could be done at that time. The cash was raised in advance and everything was paid for in cash, and it was put in practically at the lowest rate per horse power of any plant that could be built. The type of construction was not adopted as temporary, but simply because it was the best we knew about at that date. We may deal in generalities on the question of the hydraulic conduit. We cannot say that the flume or tunnel is cheaper or better. The Mt. Whitney No. 1 flume is 30,000 feet long, and a tunnel would have to be 20,000 feet long. The flume is not of large size, and therefore it can be put through at a comparatively small cost, and as the cost for the cross-section of the flume increases, the cost of its construction increases very rapidly. As a tunnel becomes larger its cost decreases very largely. We cannot generalize on those things; each case must be figured out for itself, so that I think a wrong impression is gained. The conditions that surround the Mt. Whitney plant are favorable for the long life of a flume or pole line. The average life of a flume in California is about ten years, and then its cost of maintenance becomes so very great that it is a serious tax. Then, again, we must consider the character of the country we are going through. If it is a country where the slopes are gradual, then it is all right for flume construction. It is purely a case as to whether we shall adopt a flume, or a ditch, or a tunnel, and that depends upon the country, upon its size, and also as to whether a combination of the two shall be used, using a flume where it is more difficult, and then using an open ditch where it is more favorable. In southern California we have wooden flumes that are now being replaced with reinforced concrete flumes. I will close by saying that I think some of the members have gained a wrong impression of the Mt. Whitney Company. It was started in 1898, and that is ancient history now.

F. G. Baum: Mr. Hays gives some interesting data relative to the method of making power contracts for irrigation service, which should be of use to other companies in similar service. His remarks on the character of the contracts to meet the needs, and also his remarks on the character of the construction to give the service, illustrate the principle that "local conditions" must be taken into account whenever one goes into new problems or attempts to criticize the work of others.

To say that timber face dams, wooden flumes, simply equipped power houses, wooden poles and simple substations are always wrong, and that concrete dams, elaborately equipped power houses, steel towers and elaborate substations are right, only emphasizes the fact that the man making such statements does not take into consideration all the facts. Very often we do not build more permanently for the very simple reason that the money is not available. One builds a house generally to suit his needs and his pocketbook, and a man is not a fool for building a frame house instead of a brick house. We have ferry boats to go over the water before we have tunnels to go under. We crawl before we walk.

As I stated in a paper "Some Power Transmission Economics" at the annual meeting of 1907: "In designing power transmission systems, it is always well to bear in mind that the ultimate development of the art and of the country has not yet been reached.

"In the early days of railroading, the roads and equipment were not of the present trunk-line standard. Light rails, engines and cars, and unfenced right-of-way, and unballasted roadway sufficed. To construct, at that time, up to the present standard would have meant bankruptcy. Even now the manager or engineer, who would build his branch lines of the same standard as his trunk lines, would invite a receiver to take charge of the road.

"The same conditions hold true for power plants and transmission lines. The wise manager or engineer builds to meet existing conditions, looking into the future as far as he can. He cannot afford to build duplicate plants and lines for every case, nor build all his lines on private rights-of-way with steel towers and other refinements and safeguards. He cannot afford to build a duplicate transmission line, at an additional interest cost of $5,000 per year, when the probability of an interruption, which will cause a loss of revenue of $500 per year to a consumer, is extremely remote.

"It may not be as difficult to determine the proper power station and line to build when unlimited capital and ideal power conditions exist as when there is restricted capital, limited revenue, and low-priced power at the consumer's station. Although in the latter case the amount of money to be expended may be much less than in the former, even more thought is demanded of the engineer; for in the former case, having ample resources, he builds as best he can, while in the latter he must be a judge of conditions and see far ahead, in order that the work which he builds may earn money and at the same time be capable of extension on some plan to meet the growing needs of the country and business.

"On the hydraulic construction and also on the power house and substation installation and construction, the engineer is required to devise something that will pay the largest net income in a given number of years. Sometimes he is called upon to make installations on the assumption that the plant is to be abandoned in a few years. Of course, the engineer will be criticized if he puts in a plant to meet present or apparent future needs and, due to some change in the industry or development of the country, the plant must be remodeled later. But it is the business of the engineer to solve his problems as he sees them."

Much more might be said along the same line to illustrate that construction which may be right for the New York Central R.R., or in the city of New York, may not be right for the Tonapah & Tidewater, or the town of Tonapah.

Engineers must fight the tendency to "build monuments" to themselves. Many of these "monuments" mark the death of a corporation."

Mr. Hays: As to the stream flow and the different reservoirs at power house No. 1, no provision was made for a regulating reservoir when the plant was first constructed, but afterwards, as the load was built up, we found that we had a slight peak; that was back about five years ago, before these curves showed, and we built a little reservoir there with the idea of carrying over the peak load, and as small as that was, it served its purpose very well. On the No. 2 plant, I don't know why that reservoir was put there, it was probably just put there for good measure, and probably because it was a good place for one.

On the Tule River plant we took the matter up carefully as to what size reservoir we should build. We compared the daily load curves with the daily curves of discharge of the river during low water periods and while the stream flow varied to quite an extent during the day it happens to coincide with the load curve. For instance at the height of the peak in the morning the stream flow was greatest and fell off in the evening with the load, consequently very little if any reservoir capacity was required. The reservoir was therefore built to take care of the fluctuation of the river assuming that the most unfavorable conditions were encountered or that the low water flow would occur at the time of peak load. Also the reservoir has capacity to run the plant until the steam auxiliary may be brought into commission, in case of accident to the flume.

As to the permanency of construction, of course in a case of this kind we are dealing with simple units starting from the motors right up to the power house. The average size motor on the system is a 7½ h.p.—you might say that we were doing a peddling business. The old No. 1 flume that Mr. Doble spoke of was put in for an economical reason, it was far cheaper to put in the flume than a ditch or a tunnel. The flume has been in there for twelve years, and, apparently, with the exception of being water-stained, it is still in good shape. It looks as though it had about ten years more life left in it, and there is no maintenance to speak of required on it.

On the No. 2 plant we have put in a concrete ditch. On Tule River plant we have run in a concrete ditch where the slopes would permit. We also, in that plant, have gone further than the ordinary concrete ditch and do not rely at all on the concrete or on the strength of the bank, the high water level in the ditch being just six inches above the ordinary surface of the slope of the hill. Those improvements that we have put in will eventually double the capacity of the plant, when this ditch and bank have settled down. Also, there are two very long stretches of flume on the Tule River, which some day can be cut out by putting in a tunnel. That flume is of pine, not of redwood, and probably will not last as long as the old No. 1 flume, which has been in use for the last fifteen years.

I don't think that economy could be said to figure in on any one thing with the exception of the main power line and the distributing system. They are all light stuff, all light poles, and they last very well in that country. As to the steam plants taking care of the peak loads, I believe that when the system gets a little larger by increasing the capacity of the present hydraulic plant and in carrying over the peak load by steam, that it will work out all right. Roughly, I have figures on it when the plant gets about twice its present size. We have always considered the present steam plant, simply as an auxiliary. That is a pretty heavy investment to use for that purpose, but as mentioned in the last part of the paper, the company has very much of a responsibility. We have a very large community depending upon a comparatively small power system, and if some accident should put a generating station out of business for a year, it would seriously interfere with a crop. You have to keep some auxiliary ready for all emergencies. Little interruptions do not make any difference. If the Pacific Gas and Electric Company should have its lights go out for fifteen minutes between six and seven o'clock at night, it would be a serious matter. For ours to go out between six and seven at night about half of one per cent of the consumers would pay their bill next month and make a "kick" about it.

As to the protection of the motors: That has been one of the things we have been trying very hard to arrange for, and, the only practicable apparatus we can furnish is just a straight circuit-breaker, so that when the current goes off, the motor stops, and when the power comes on again, it will trip the circuit-breaker. The average farmer objects to even putting that protection on. All he wants is a fuse. In fact, last year some of our consumers held an indignation meeting because they understood we were obliging them to put on circuit breakers, and they said they would not do it. They held a meeting, and decided that we were trying to get $36 more out of them and they would not stand for it. In fact, we had more trouble with them about that, than we have with them about the contracts. We get them to sign the contracts, sometimes they object, but the contract is absolutely fair. We have to give them a cheap rate, but we work on practically a cash basis. The penalty of one per cent per month provided in the contract is no joke. We actually enforce it, and yet it is not an unusual thing for a man to wait until the end of the year before he pays his bill. Some consumers prefer to pay that one per cent per month interest, and so we allow them to wait until the end of the year.

In operating a pump station I don't know of a single instance in that section where labor costs have been counted. A man generally does the work himself, oils up his pump and looks at his motor about twice a day, goes down into the field, and if the water stops he goes back and finds out what is the matter.

As to the secretary's reference to the underground water, I will say that I do not know of any cases in that section where they have dug for water and did not find it. Some of the growers tried to go up too far into the mountains and there were some wells there that were abandoned after they struck rock, bed rock and granite, and some of them, I presume, never would have reached water.

We have something better for the eastern tenderfoot than the dry lands. We have the "white ash" land, or that which is generally known as alkali land down there, and that sells very well to easterners, and there is more profit in it.

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PARALLEL OPERATION OF THREE-PHASE GENERATORS, WITH THEIR NEUTRALS INTERCONNECTED

BY GEORGE I. RHODES

The difficulty of operating three-phase star-connected generators, with their neutrals in parallel, was most forcibly brought to the attention of the engineering profession when the company with which the writer is connected attempted to operate its plants in that manner. The various phenomena of that attempt have been fully described by C. W. Ricker (Experience with a Grounded Neutral on a High-Tension Plant, *Electric Journal*, September, 1906) and by the writer (Experience with a Grounded Neutral on the High Tension System of the Interborough Rapid Transit Company, TRANSACTIONS of American Institute of Electrical Engineers, Vol. XXVI, Part II, page 1605).

The subject of neutral currents has been discussed considerably. It is generally understood that they are of triple frequency and are produced by those harmonics of e.m.f. which cannot exist between the lines of a three-phase system. A general review of the theory of these phenomena may not be out of place.

Consider a three-phase star-connected generator (Fig. 1) in whose windings e.m.fs. are generated containing triple harmonics. The e.m.fs. in the coils differ in phase 120 fundamental degrees. The third harmonics differ 3×120 = 360 third harmonic degrees; the ninth harmonics, 9×120 = 1080 ninth harmonic degrees. The triple harmonics are thus in phase in all three coils. Since the potential difference between the outer terminals of two windings is equal to the vector difference between the e.m.fs. generated in the coils, the triple harmonics being in phase, will disappear. Thus, in a three phase star-connected system no triple harmonic voltages can exist between the lines.

The higher harmonics, other than multiples of the third, are not eliminated in the voltage between phases. They appear in the same relative magnitudes as in the coil voltages.

If this generator is connected to a balanced star-connected load, currents will flow in the lines of such wave form and magnitude that the potential differences between the terminals and the neutral point will differ from the coil e.m.fs. only by containing no triple harmonics. There can be no currents of these frequencies because they would be in phase in all three lines and hence could have no return path. It is evident that there will exist between the neutral of the generator and that of the load a voltage made up of the triple harmonics generated in the coils of the alternator. If these points are connected, currents of corresponding frequency will flow. The current in this interconnection will be three times the triple frequency current in the lines.

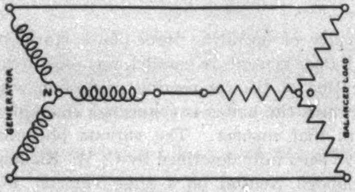

Fig. 1

If, instead of a load, another generator is connected to the first, a difference of potential will exist between their neutrals, equal to the vector difference between their coil e.m.fs. With the neutrals interconnected, a current will flow, limited by the impedances of the machines to triple harmonics. These impedances are in general much smaller than the synchronous impedances.

If the triple frequency e.m.fs. in the two machines are equal and in phase, there can be no neutral potential or current. This ideal condition can exist in general only when one or more of the following conditions are observed.

1. Equal instantaneous angular velocities.
2. Similar wave forms.

3. Equal loads.
4. Excitations corresponding to the loads.
5. Absence of all triple harmonics.

In all reciprocating machines the angular velocity pulsates to a greater or less extent. It has been found by experience that this surging is more troublesome in producing neutral currents than interchange between the phases. Machines that will operate very satisfactorily without neutral connections have caused serious trouble when operated with them. The obvious preventative for trouble of this kind is more uniform rotation, namely, the use of steam turbines or water driven prime movers.

Machines frequently differ considerably in wave form. They may be similar at no load, but differ when loaded on account of armature reaction. Attempts to operate generators thus differing, have resulted in enormous neutral currents. The preventative in this case is careful adjustment of wave forms.

Generators may have e.m.fs. similar to each other at all loads, yet the wave forms at any two different loads may be dissimilar. Machines thus operated at unequal loads will show neutral voltages or currents. These load differences are easily controlled, except in the case of surging mentioned above, so that no trouble should arise. At the instant of synchronizing, however, the load difference is a maximum and serious trouble may occur. Difficulty of this kind has made the operation of synchronizing impossible with several generators on the line. The obvious preventative is to close the neutral connection after the loads are adjusted.

Another cause of dissimilarity in wave form is that excitations, or field currents, are not correctly adjusted to the loads. These differences are of small magnitude and the neutral currents are of no importance under ordinary conditions. They may be reduced by a careful adjustment of excitation.

In all of the above cases the interchange of triple harmonic current may be reduced by the insertion of impedances in the neutral connections. These impedances may be undesirable on account of their size, or on account of the voltage drop in case of unbalanced load. The neutral currents may be eliminated by the connection of but a single generator to the neutral bus, but this method has its limitations. If more than one generator must be operated with a neutral connection, and if impedances are undesirable, then the only remedy is to obtain machines generating no triple harmonic e.m.fs.

It is the purpose of the following discussion to show the real cause of triple harmonics, to indicate a method of computing them, a method of measuring them, and finally to suggest certain elements of design which will reduce them to a negligible amount.

GENERAL EQUATIONS

In any alternator the field or excitation m.m.f. at any point in the air gap may be represented by the following equation:

$$\mathfrak{F}_f = f_1 \sin \alpha + f_3 \sin 3\alpha + \ldots\ldots + f_m \sin m\alpha$$
$$+ g_1 \cos \alpha + g_3 \cos 3\alpha + \ldots\ldots + g_m \cos m\alpha$$
$$= \sum_1^m f_m \sin m\alpha + \sum_1^m g_m \cos m\alpha$$

where

$\mathfrak{F}_f$ = excitation m.m.f. at any point along air gap

$f_1, f_3, \ldots\ldots f_m$ = coefficients of sine terms.

$g_1, g_3, \ldots\ldots g_m$ = coefficients of cosine terms

m = index of harmonic.

α = angular distance of point from interpolar axis (Fig. 2).

It is evident that this equation takes into account all cases where the excitations of the poles are equal, whether the windings are concentrated in a single field coil or are distributed over the polar surface.

A similar equation represents the average value of the m.m.f. of armature reaction of any polyphase alternator, thus

$$\mathfrak{F}_a = a_1 \sin \alpha + a_3 \sin 3\alpha + \ldots\ldots + a_n \sin n\alpha$$
$$+ b_1 \cos \alpha + b_3 \cos 3\alpha + \ldots\ldots + b_n \cos n\alpha$$
$$= \sum_1^n a_n \sin n\alpha + \sum_1^n b_n \cos n\alpha$$

where

$\mathfrak{F}_a$ = armature reaction m.m.f. at any point along air gap.

$a_1, a_3, \ldots\ldots a_n$ = coefficients of sine terms.

$b_1, b_3, \ldots\ldots b_n$ = coefficients of cosine terms

n = index of harmonic.

α = angular distance of point from interpolar axis.

This equation does not take into account the fluctuations of reaction which are present in all armatures except the ideal with an infinite number of phases.

In most alternators a suitable wave form is secured by a greater or less variation in the shape of the pole pieces and hence, in the length of the air gap. This variation in reluctance at different points may be represented by the following equation.

$$K = \pm k_1 \sin \alpha \pm k_3 \sin 3\,\alpha \pm \;.\;.\;.\;.\;.\; \pm k_p \sin p\,\alpha$$

$$\pm l_1 \cos \alpha \pm l_3 \cos 3\,\alpha \pm \;.\;.\;.\;.\;.\;.\; \pm l_p \cos p\,\alpha$$

$$= \pm \sum_1^p k_p \sin p\,\alpha \pm \sum_1^p l_p \cos p\,\alpha$$

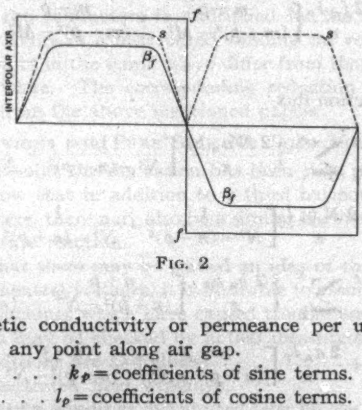

FIG. 2

where

K = magnetic conductivity or permeance per unit angle at any point along air gap.

$k_1, k_3, \ldots\ldots k_p$ = coefficients of sine terms.

$l_1, l_3, \ldots\ldots l_p$ = coefficients of cosine terms.

p = index of harmonic.

α = angular distance of point from interpolar axis.

In this equation the positive sign holds from $\alpha = 0$ to $\alpha = \pi$ and the negative from $\alpha = \pi$ to $\alpha = 2\pi$ etc. This change of sign is necessary as the permeance must be positive in value at all points.

We now have three general equations representing the variation in permeance and in magnetomotive forces of excitation and armature reaction along the air gap of the ideal polyphase alternator.

The corresponding flux densities may be computed by multiplying the magnetomotive forces into the permeance and reducing to new series. These series are here given for future reference.

No load flux

$$\beta_f = \sum_1^m \sum_1^p \sum_1^M \left\{ \frac{2\,M\,f_m\,k_p}{\pi} \left[\frac{1}{M^2-(m-p)^2} - \frac{1}{M^2-(m+p)^2} \right] \right.$$

$$\left. + \frac{2\,M\,g_m\,l_p}{\pi} \left[\frac{1}{M^2-(m-p)^2} + \frac{1}{M^2-(m+p)^2} \right] \right\} \sin M\,\alpha$$

$$+ \sum_1^m \sum_1^p \sum_1^M \left\{ \frac{2\,g_m\,k_p}{\pi} \left[\frac{m+p}{(m+p)^2-M^2} - \frac{m-p}{(m-p)^2-M^2} \right] \right.$$

$$\left. + \frac{2\,f_m\,l_p}{\pi} \left[\frac{m+p}{(m+p)^2-M^2} + \frac{m-p}{(m-p)^2-M^2} \right] \right\} \cos M\,\alpha \tag{I}$$

Armature reaction flux

$$\beta_a = \sum_1^n \sum_1^p \sum_1^N \left\{ \frac{2\,N\,a_n\,k_p}{\pi} \left[\frac{1}{N^2-(n-p)^2} - \frac{1}{N^2-(n+p)^2} \right] \right.$$

$$\left. + \frac{2\,N\,b_n\,l_p}{\pi} \left[\frac{1}{N^2-(n-p)^2} + \frac{1}{N^2-(n+p)^2} \right] \right\} \sin N\,\alpha$$

$$+ \sum_1^n \sum_1^p \sum_1^N \left\{ \frac{2\,b_n\,k_p}{\pi} \left[\frac{n+p}{(n+p)^2-N^2} - \frac{n-p}{(n-p)^2-N^2} \right] \right.$$

$$\left. + \frac{2\,a_n\,l_p}{\pi} \left[\frac{n+p}{(n+p)^2-N^2} + \frac{n-p}{(n-p)^2-N^2} \right] \right\} \cos N\,\alpha \tag{II}$$

where all symbols have the same significance as above, with the addition of

M = index of harmonic in field flux.

N = index of harmonic in reaction flux.

These equations may be transformed to represent voltages by a method explained in great detail by Comfort A. Adams in his paper " The Voltage Ratio in Synchronous Converters with Special Reference to the Split Pole Converter," TRANSAC-

TIONS A.I.E.E., Vol. XXVII, Part II, page 959, and "Electromotive Force Wave Shape in Alternators," TRANSACTIONS A.I.E.E., Vol. XXVIII, Part II, page 1053.

In brief, the method is as follows. A single conductor passing at a uniform velocity through a flux whose distribution may be represented by a Fourier's Series, a wave of e.m.f. is generated exactly similar in form. The relative values of the different harmonics are the same in the e.m.f. wave as in the flux distribution wave. If, however, instead of a single coil, a number of similarly distributed windings are passed through the flux, the net e.m.f. generated is the vector sum of the e.m.fs. in the individual coils. This vector sum is less than the arithmetical sum by a proportion depending on the angular space over which the coils are distributed; the greater the space the greater the reduction. In the case of the higher harmonics the angular distribution of the conductors is multiplied by the index of the harmonics. Hence in a distributed winding the relative values of the harmonics in the e.m.f. wave differ from those in the flux distribution wave. The corresponding reduction factors may be obtained from the above mentioned papers.

EQUATIONS FOR PURE SINE NO LOAD VOLTAGE

Up to this point the discussion has been very general. The equations show that in addition to a third harmonic in the no load e.m.f. wave, there may also be a similar harmonic generated by the armature reaction.

In order that there may be gained an idea of the real magnitudes of the neutral voltages, it is desirable to assume conditions existing in machines which have caused trouble and to compute figures which may be checked by actual measurement.

These conditions are as follows:

1. Concentrated field windings.
2. Armature windings distributed over 60 electrical degrees per phase.

The first condition obtains in by far the greater number of machines. The second in most machines of large size, where it has been found desirable to use a full pitch winding.

For preliminary computations, it will be assumed that no triple harmonic exists in the no load coil e.m.f. wave of the generator; that is, the potential between line and neutral is purely sinusoidal. It will also be assumed that the armature reaction m.m.f. is purely sinusoidal, as would be the case with a machine of an infinite number of phases.

We thus have for the m.m.f. due to excitation,

$$\mathfrak{F}_f = \pm f$$

That is, the magnetomotive force is uniform over the polar space, being positive between $\alpha = 0$ and $\alpha = \pi$ and negative from $\alpha = \pi$ to $\alpha = 2\,\pi$. This assumption is not completely borne out in practice, but it is near enough for purposes of approximation.

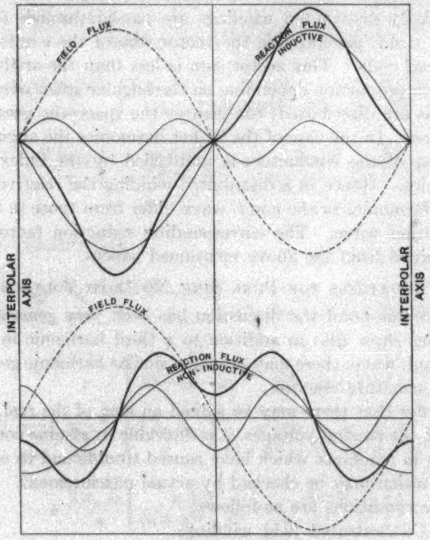

FIG. 3

The m.m.f. due to armature reaction is

$$\mathfrak{F}_a = a_1 \sin \alpha + b_1 \cos \alpha$$

$$a_1^2 + b_1^2 = A_1^2$$

The sine terms represent the effect of current in quadrature with the internal e.m.f. and the cosine terms that of current in phase with it. Thus

$$\mathfrak{F}_a = A_1 \sin \phi \sin \alpha - A_1 \cos \phi \cos \alpha$$

where ϕ = angle between current and internal e.m.f.

The magnetic conductance or the permeance in the air gap is represented as follows:

$$K = \pm k_1 \sin \alpha$$

The field flux is easily obtained as follows:

$$\beta_f = \mathfrak{F}_f\, K = f\, k_1 \sin \alpha$$

The reaction flux distribution is derived by substituting in equation (II).

$$n = 1,\ p = 1,\ l = 0 \text{ and } N = 1,\ 3$$

$$\beta_a = k_1\, A_1 \sin \phi\ (0.848 \sin \alpha - 0.170 \sin 3\, \alpha\ \ldots\ldots)$$

$$- k_1\, A_1 \cos \phi\ (0.424 \cos \alpha - 0.254 \cos 3\, \alpha\ \ldots\ldots)$$

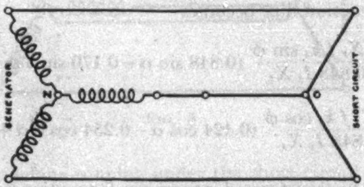

FIG. 4

The relative values and phases of these reaction fluxes are shown in Fig. 3. The upper curves show the reaction due to a current lagging 90 deg. behind the internal voltage and the lower curves that due to an equal current in phase therewith. It will be seen that the armature reaction causes triple harmonic fluxes of from 20 per cent to 60 per cent of the total.

Considering the case of a machine running under short circuit conditions as represented in Fig. 4, the current lags practically 90 deg. behind the internal e.m.f. generated by the excitation flux. A triple harmonic voltage appears between the neutral of the generator and the short circuit point. That portion of the field flux of fundamental distribution not required to generate e.m.fs. overcoming the leakage impedance drop, is neutralized by the corresponding reaction flux.

We thus have the following relation

$$f\,k_1\,\frac{X_r}{X_s}\quad.\ +0.848\,k_1\,A_1 \sin\left(-90°\right)=0$$

$$A_1=\frac{f\,X_r}{0.848\,X_s}$$

where X = leakage reactance.
X_r = reaction reactance.
X_s = synchronous reactance.
Under conditions other than short circuit if
I = current.
I_s = short circuit current.

$$A_1=\frac{I\,X_r\,f}{0.848\,I_s\,X_s}$$

Thus the reaction flux becomes

$$\beta_a=\frac{I\,X_r\,f\,k_1 \sin\phi}{0.848\,I_s\,X_s}\left(0.848 \sin\alpha-0.170 \sin 3\,\alpha+\ .\ \ .\right)$$

$$-\frac{I\,X_r\,f\,k_1 \cos\phi}{0.848\,I_s\,X_s}\left(0.424 \cos\alpha-0.254 \cos 3\,\alpha+\ .\ \ .\right)$$

This may be transformed into an e.m.f. equation by the method referred to above, with a reduction factor of $\frac{2}{3}$ for the third harmonic.

If e_f = instantaneous value of internal e.m.f.
E_f = effective value of internal e.m.f.
e_a = instantaneous value of reaction.
E_a = effective value of reaction e.m.f.
$\omega = 2\,\pi$ times frequency.
t = time.

Since

$$e_f=\sqrt{2}\,E_f \sin\omega\,t$$

$$e_a=\frac{\sqrt{2}\,E_f\,I\,X_r \sin\phi}{0.848\,I_s\,X_s}\left(0.848 \sin\omega\,t-0.113 \sin 3\,\omega\,t+\ .\ \ .\right)$$

$$-\frac{\sqrt{2}\,E_f\,I\,X_r \cos\phi}{0.848\,I_s\,X_s}\left(0.424 \cos\omega\,t-0.169 \cos 3\,\omega\,t+\ .\ \ .\right)$$

Since $I_s X_s = E_f$

$$e_a = 1.18\sqrt{2}\, I\, X_r\, [(0.848 \sin \omega t - 0.113 \sin 3\, \omega t) \sin \phi$$

$$- (0.424 \cos \omega t - 0.169 \cos 3\, \omega t\, .\, .) \cos \phi$$

The magnitude of the triple harmonic voltage may be calculated readily from this equation. For instance, in a machine whose load current is one-half the short circuit current and whose leakage reactance is negligible, its value may readily reach at unity power factor.

$$\frac{1.18 \times 0.169\, E_f}{2} = 0.10\, E_f$$

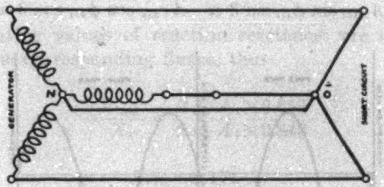

Fig. 5

With the machine running under the short circuit conditions shown in Fig. 5, a triple harmonic current flows in the neutral connection.

The impedance which the armature winding offers to the flow of this current is made up of two items; that due to leakage flux and that due to reaction flux. It is evident that the leakage flux is the same, irrespective of whether the current is of fundamental or of triple frequency. The distribution and the magnitude of the reaction flux produced by triple harmonic currents, differ in a marked degree from that produced by a fundamental current.

If X_{III} = leakage reactance to third harmonic current.

$X_{r\text{III}}$ = reaction reactance of third harmonic current.

$X_{s\text{III}}$ = total reactance of third harmonic current.

The leakage flux is independent of the frequency, thus

$$X_{\text{III}} = 3\, X$$

Since the triple harmonic currents are in phase in all three armature coils, the reaction m.m.f. has a triple distribution corresponding to three times the normal number of poles (Fig. 6). This magnetomotive force may be represented by the following equation.

$$\mathcal{F}_{a\,\mathrm{III}} = \sum_1^n a_{n\,\mathrm{III}} \sin 3\,n\,\alpha + \sum_1^n b_{n\,\mathrm{III}} \cos 3\,n\,\alpha$$

The m.m.f. multiplied into the permeance gives the reaction flux produced by the triple harmonic.

Considering only the simple conditions enumerated in the foregoing computations

$$\mathcal{F}_{a\,\mathrm{III}} = a_{1\,\mathrm{III}} \sin 3\,\alpha + b_{1\,\mathrm{III}} \cos 3\,\alpha$$

$$= A_{1\,\mathrm{III}} \sin \phi_{\mathrm{III}} \sin 3\,\alpha - A_{1\,\mathrm{III}} \cos \phi_{\mathrm{III}} \cos 3\,\alpha,$$

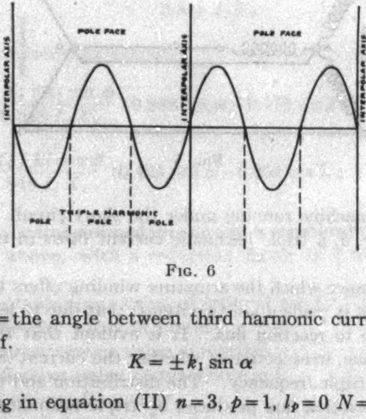

FIG. 6

where ϕ_{III} = the angle between third harmonic current and internal e.m.f.

$$K = \pm k_1 \sin \alpha$$

Substituting in equation (II) $n=3$, $p=1$, $l_p=0$ $N=1, 3$,

$$\beta_{a\,\mathrm{III}} = k_1 A_{1\,\mathrm{III}} \sin \phi_{\mathrm{III}} (-0.170 \sin\ \alpha + 0.655 \sin 3\,\alpha)$$
$$-k_1 A_{1\,\mathrm{III}} \cos \phi_{\mathrm{III}} (-0.255 \cos \alpha + 0.618 \cos 3\,\alpha)$$

On account of the triple distribution of the m.m.f., the magnitude of this flux, is but $\frac{1}{3}$ of that produced by an equal fundamental current. The increased angular distribution of the armature windings has a similar influence on the flux as on the e.m.f. This increase is from 60 deg. to 180 deg, with a corresponding reduction factor of approximately $\frac{2}{3}$.

Thus

$$A_{1\,\text{III}} = \frac{2}{9} A_1,$$

With the neutrals short circuited, the triple harmonic reaction flux distribution is

$$\beta_{a\text{III}} = \frac{2}{9} k_1 A_1 \,(0.655 \sin 3\,\alpha)$$

An equal fundamental current produces a reactance flux distribution

$$\beta_a = k_1 A_1 \,(0.848 \sin \alpha)$$

The relative values of reaction reactances are the same as those of the corresponding fluxes, thus

$$\frac{X_{r\text{III}}}{X_r} = \frac{2\, k_1 A_1 \times 0.655}{9\, k_1 A_1 \times 0.848}$$

$$X_{r\text{III}} = 0.171\, X_r$$

It will be noted that the triple harmonic current develops a small fundamental reaction aiding the excitation. This is negligible, however, for a neutral current three times the line short circuit current has an effect of only 2/9×0.170=3.8 per cent of the excitation.

Summarizing the equations which have thus far been deduced, we have for conditions of pure sine distribution of no load flux,

Triple harmonic or neutral e.m.f.

$$e_{\text{III}} = -1.18 \sqrt{2}\, I\, X_r \,[0.113 \sin \phi \sin 3\,\omega\, t - 0.169 \cos \phi \cos 3\,\omega\, t]$$

Reactance per phase for neutral current.

$$X_{s\text{III}} = 3\, X + 0.171\, X_r$$

EQUATIONS FOR MACHINE WHOSE NO LOAD VOLTAGE CONTAINS A THIRD HARMONIC

In most alternators there is present at no load a triple frequency e.m.f. which flattens the wave form symmetrically. This harmonic thus has a positive value, as referred to the fundamental. The following equations represent the various quantities taking into account this no load neutral voltage.

Excitation m.m.f.

$$\mathfrak{F}_f = \pm f$$

Armature reaction m.m.f.

$$\mathfrak{F}_a = A_1 \sin \phi \sin \alpha - A_1 \cos \phi \cos \alpha$$

Permeance of air gap

$$K = \pm\, k_1 \sin \alpha \pm k_3 \sin 3\,\alpha = \pm\, k_1 \left(\sin \alpha + \frac{k_3}{k_1} \sin 3\,\alpha \right)$$

Reaction flux distribution

$$\begin{aligned}\beta_a = k_1\, A_1 \sin \phi & \left[\left(0.848 - 0.17 \frac{k_3}{k_1} \right) \sin \alpha \right. \\ & \left. - \left(0.170 - 0.65 \frac{k_3}{k_1} \right) \sin 3\,\alpha \right] \\ - k_1\, A_1 \cos \phi & \left[\left(0.424 + 0.60 \frac{k_3}{k_1} \right) \cos \alpha \right. \\ & \left. - \left(0.254 - 0.11 \frac{k_3}{k_1} \right) \cos 3\,\alpha \right]\end{aligned}$$

Relation between A_1 and f_1

$$A_1 = \frac{f_1\, X_r}{\left(0.848 - 0.17 \frac{k_3}{k_1} \right) X_s}$$

Open circuit or internal voltage

$$e_f = \sqrt{2}\, E_f \left(\sin \omega t + \frac{E_{f\mathrm{III}}}{E_f} \sin 3\,\omega t \right)$$

Now

$$\frac{k_3}{k_1} = \frac{3\, E_{f\mathrm{III}}}{2\, E_f}$$

on account of the voltage reduction factor.

Armature reaction voltage,

$$e_a = \frac{\sqrt{2}\ I\ X_r}{0.848 - 0.25\,\dfrac{E_{f\,\mathrm{III}}}{E_f}} \left\{ \left[\left(0.848 - 0.25\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \sin \omega\, t \right.\right.$$

$$\left. - \left(0.113 - 0.65\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \sin 3\,\omega\, t \right] \sin \phi$$

$$- \left[\left(0.424 - 0.90\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \cos \omega\, t \right.$$

$$\left.\left. - \left(0.170 - 0.11\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \cos 3\,\omega\, t \right] \cos \phi \right\}$$

Third harmonic reaction flux

$$\beta_{a\,\mathrm{III}} = k_1\ A_{\mathrm{III}} \left\{ \left[\left(-0.170 + 0.97\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \sin \alpha \right.\right.$$

$$\left. + \left(0.655 + 0.42\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \sin 3\,\alpha \right] \sin \phi_{\mathrm{III}}$$

$$- \left[\left(-0.255 + 0.17\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \cos \alpha \right.$$

$$\left.\left. + \left(0.618 + 0.21\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \cos 3\,\alpha \right] \cos \phi_{\mathrm{III}} \right\}$$

Total third harmonic reactance

$$X_{s\,\mathrm{III}} = 3\ X + \frac{2\left(0.655 + 0.42\,\dfrac{E_{f\,\mathrm{III}}}{E_f}\right) X_r}{9\left(0.848 - 0.25\,\dfrac{E_{f\,\mathrm{III}}}{E_f}\right)}$$

Summarizing the equations, triple frequency e.m.f.

$$e_{\mathrm{III}} = \sqrt{2}\ E_{f\,\mathrm{III}} \sin 3\,\omega\, t - \frac{\sqrt{2}\ I\ X_r}{0.848 - 0.25\,\dfrac{E_{f\,\mathrm{III}}}{E_f}} \left\{ \right.$$

$$\left(0.113 - 0.65\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \sin 3\,\omega\, t \sin \phi$$

$$\left. - \left(0.170 - 0.11\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) \cos 3\,\omega\, t \cos \phi \right\} \qquad \text{(III)}$$

Triple frequency reactance per phase

$$X_{s\,\mathrm{III}} = 3\,X + \frac{2\left(0.655 + 0.42\,\frac{E_{f\,\mathrm{III}}}{E_f}\right) X_r}{9\left(0.848 - 0.25\,\frac{E_{f\,\mathrm{III}}}{E_f}\right)} \qquad \text{(IV)}$$

Where

e_{III} = instantaneous value of neutral voltage.
$E_{f\,\mathrm{III}}$ = effective value of no load neutral voltage.
E_f = effective value of no load coil voltage.
I = load current.
ϕ = angle between current and internal voltage.
X = leakage reactance per phase fundamental.
X_r = reaction reactance per phase fundamental.

These equations apply to all generators having full pitch coils distributed over 60 electrical degrees per phase, with a wave form secured by varying the air gap. This type of machine is quite common.

DETERMINATIONS OF ANGLE BETWEEN LOAD CURRENT AND INTERNAL E.M.F.

In all of the above equations for triple harmonic voltages there is present the undetermined angle between the load current and the internal e.m.f. due to excitation. Referring to Fig. 3 it will be noted that the reaction due current in phase with the internal e.m.f. is practically one-half that due to an equal current in quadrature therewith. Under these conditions the terminal voltage is approximately

$$P\,D = E_f\left(1 + \frac{I}{I_s}\sin\phi - j\,\frac{I}{2\,I_s}\cos\phi\right)$$

If ψ = the angle between the terminal and the internal e.m.f.s

$$\psi = \tan^{-1}\frac{-\frac{I}{I_s}\cos\phi}{2\left(1 + \frac{I}{I_s}\sin\phi\right)}$$

If θ = the angle between the current and the terminal voltage

$$\theta = \phi - \psi$$

These equations may be solved to get ψ when the load and power factor are known. The approximate values may be obtained readily from Fig. 7. In this figure the abscissæ represent angles between the current and the terminal voltage and the ordinates angles between the terminal and internal voltages. Negative angles signify that the current lags behind the terminal voltage or the terminal voltage behind the internal voltage.

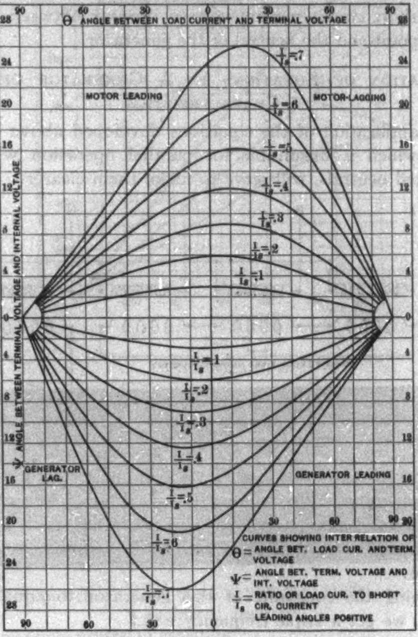

FIG. 7

MEASUREMENT OF TRIPLE HARMONICS

In the foregoing discussion it is assumed that we have a means of measuring the no load third harmonic. The method is as follows. (Fig. 8). Connect three transformers with the primaries in star and the secondaries in delta. The triple harmonic necessary for the magnetizing currents cannot flow in the lines; they appear as circulating currents in the delta windings. The delta connection also equalizes the voltages on all three transformers, so that the neutral of the primary connection is the true neutral of the system. A voltmeter, either alone or with a potential transformer connected between the transformer neutral and the generator neutral, will indicate the magnitude of the triple harmonic voltages. An oscillograph will give the phase relations.

The short circuit neutral voltages appear between the short circuit point and the neutral of the generator.

APPLICATION OF EQUATIONS TO A GENERATOR OF KNOWN CHARACTERISTICS

The application of the equations developed above to a generator which is unsuitable for parallel operation with interconnected neutrals, will serve to make them clearer.

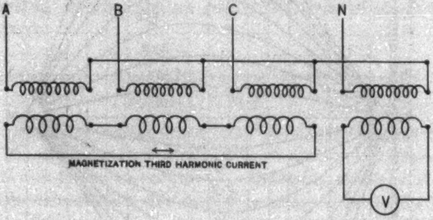

FIG. 8

In Figs. 9 and 10 are shown the no-load characteristics of such a generator. The winding is a distributed full pitch winding of usual type. It will be observed that the open circuit triple harmonic is symmetrical with the coil voltage and positive in value.

Applying the constants of this generator to equations III and IV, we get a triple frequency e.m.f.

$$\begin{aligned} e_{III} &= 0.085\,E_f\sqrt{2}\sin 3\,\omega\,t - \frac{I\,X_r\sqrt{2}}{0.848-0.25\times0.085}\left\{\begin{aligned}&(0.113-0.65\times0.085)\sin 3\,\omega\,t\sin\phi\\ &-(0.170-0.11\times0.085)\cos 3\,\omega\,t\cos\phi\end{aligned}\right\} \\ &= 0.085\,E_f\sqrt{2}\sin 3\,\omega\,t - 0.069\,I\,X_r\sqrt{2}\sin 3\,\omega\,t\sin\phi \\ &\qquad + 0.195\,I\,X_r\sqrt{2}\cos 3\,\omega\,t\cos\phi \end{aligned}$$

Triple frequency reactance per phase

$$X_{s\text{III}} = 3\times 0.8 + \frac{2\,(0.655+0.42\times 0.085)\,X_r}{9\,(0.848-0.25\times 0.085)} = 2.4+0.185\,X_r$$

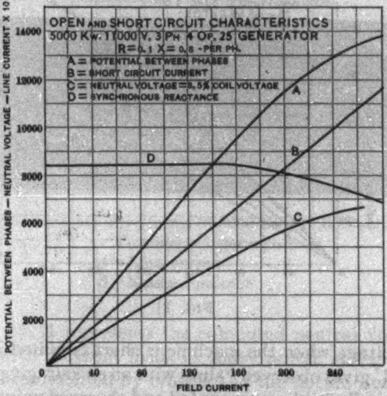

FIG. 9

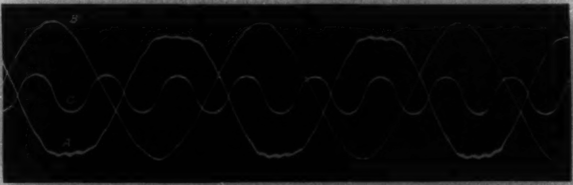

FIG. 10.—Open circuit wave forms of 5000 kw., 11,000-volt, three-phase, Y-connected generator

A = Line to neutral of generator
B = Line to line
C = Neutral of generator to neutral of system

If this machine had no neutral voltage on open circuit, these equations would be

$$e_{\text{III}} = -0.133\,I\,X_r\sqrt{2}\sin 3\,\omega\,t\sin\phi + 0.200\,I\,X_r\sqrt{2}\cos\omega\,t\cos\phi$$

$$X_{s\text{III}} = 2.4+0.174\,X_r$$

Figs. 11, 12 and 15 show the effective values of voltage and current as represented by these equations, together with observed values. In Fig. 11, *A* represents the computed values of neutral voltage when the machine is short circuited in the usual manner; *A′* gives observed values with an encouraging agreement. *B* and *B′* similarly show computed and observed values of neutral current when the neutral also is connected to the short circuit point. The agreement here is not quite as good, but is still quite satisfactory.

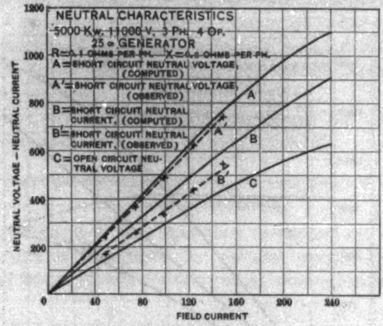

Fig. 11

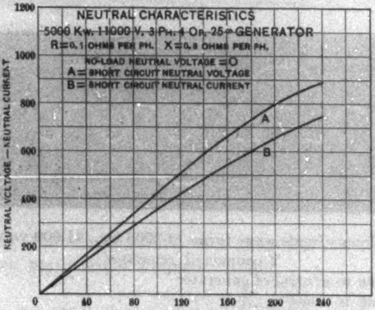

Fig. 12

Fig. 12 shows the magnitudes of neutral voltage and current that would have obtained in this machine, had its pole faces been shaped to give a sine wave when run on open circuit.

Figs. 13 and 14 are reproductions of oscillograph records taken under short circuit conditions. They are self-explanatory.

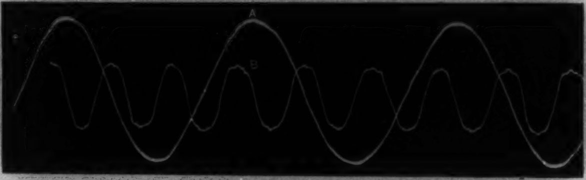

FIG. 13.—Short circuit wave forms of 5000-kw., 11,000-volt, three-phase, Y-connected generator

A = Line current

B = Neutral voltage

In Fig. 15, *A* represents the computed neutral voltage of the machine with different loads at unity power factor. Observed values are represented by crosses and the dotted line. *B* shows what these voltages would be in a similar machine with a perfect wave form at no load.

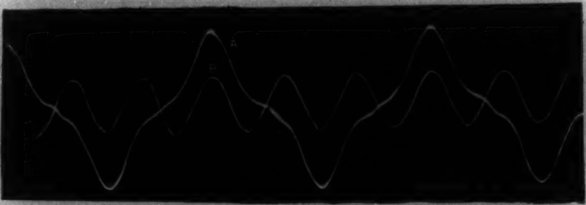

FIG. 14.—Short circuit wave forms of 5000-kw., 11,000-volt, three-phase, Y-connected generator

A = Line current

B = Neutral current

The discrepancy at overloads is probably due to the fact that the air gap between the poles has a greater permeance in actual machines than in the ideal machine upon whose characteristics the equations are based. This increased permeance has the result of greatly reducing the triple harmonic caused by the reaction of current in phase with the internal voltage. The reduction is to approximately one-third of the calculated value, which magnitude gives calculated curves corresponding to the observed values.

The above comparisons of observed and computed results are given as a test of the theory and methods. The further application to difference in potential, etc., between the neutrals of machines in parallel will serve as a measure of trouble to be expected.

In Fig. 15, curves *C* and *B* show the calculated voltage between the neutrals of two machines, one of which is running without load and the other of which is running loaded. The voltage between neutrals of two machines is governed principally by the reaction of inductive load, hence the effect of the reduction of interpolar triple harmonics mentioned in connection with Fig. 15 is of comparatively little importance.

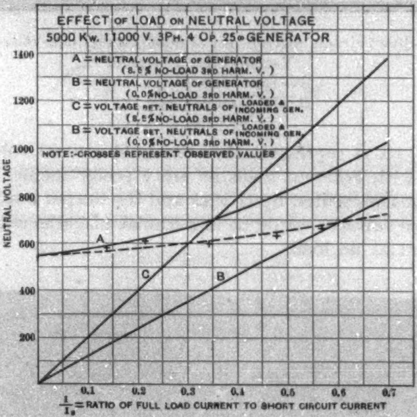

Fig. 15

Fig. 16 shows the calculated angular displacement of voltages due to load. *A* shows the angular displacement of the internal voltage; *B* the angular displacement of the neutral voltage and *C* the angular displacement of neutral voltage in a machine having zero no load triple harmonic.

It will be observed that the triple harmonic is displaced by an angle several times as great as is that of the fundamental. It will also be observed that at large loads the voltage between neutrals of loaded and unloaded generators may be larger than the neutral voltage of either, due to the very large angular displacement.

Figs. 17 and 18 are oscillograph records taken on a machine running at loads of 5000 and 9000 kw. These loads correspond to ratios of approximately 0.32 and 0.58. These records show a reasonably close agreement with theory as to the angular displacement of the neutral voltage.

In the early part of the paper it was mentioned that the causes of trouble with similar machines were non-uniform angular velocities and unequal loads. Referring to Fig. 15, curve *C*, it is seen that the voltage between the neutral of a loaded generator and that of an unloaded generator is practically a linear function of the load. Thus, two machines running with different loads would have about the same neutral potential difference as though one of them were loaded by an amount equal to the load difference and the other was running unloaded.

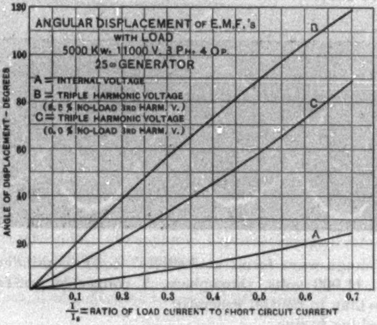

FIG. 16

Unequal instantaneous velocities result directly in a surging of load between two machines. This surging at times amounts to a load corresponding to $I/I_s = 0.25$. This is unusual, but nevertheless is encountered even in well designed plants having reciprocating engines. With generators, such as have given trouble, this causes a neutral potential difference of 500 volts.

The triple frequency reactance being 3.7 ohms per phase, there would flow in the interconnected neutrals of two machines a current of $\frac{500\times 3}{2\times 3.7}=202$ amperes. With a large number of machines interconnected, this current could amount to 400 amperes.

Currents of these magnitudes are not in themselves large enough to cause serious trouble, but since they are always present as surges their possible effects on a large system are somewhat alarming.

It has been found in practice that at times there would be a more or less sudden excessively large rush of current, due possibly to the valve mechanism of the engine. Any such sudden large variation in angular velocity would produce a current limited, not by reactance computed above, but by the leakage reactance without iron. This may not exceed 20 per cent of the leakage reactance, or, in the machines considered above, 0.48 ohms per phase. Under these conditions surges may occur as large as $\frac{500\times 3}{0.48}=3100$ amperes.

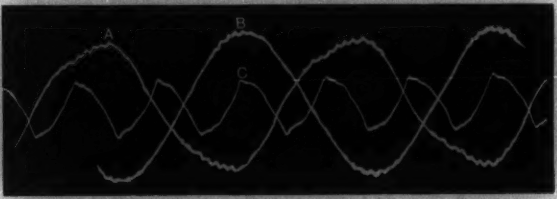

FIG. 17.—Voltage wave forms at 5000-kw., load (non-inductive) 5000-kw., 11,000 volts, three-phase, Y connected generator
A = Line to neutral generator
B = Line to line
C = Neutral of generator to neutral of system

An inspection of Fig. 15 shows that little improvement may be expected by designing the machine with a perfect no load voltage.

Most serious difficulty in the operation of generators with interconnected neutrals has been during the operation of synchronizing. At this time there is a very large difference in loads and at the instant of closing the switch there is a sudden short circuit of the neutral voltage. Loads may differ at this time as much as $I/I_s=0.6$. corresponding to a neutral voltage of 1190 volts. The first rush of neutral current with several machines running, may reach $\frac{1190\times 3}{0.48}=7450$ amperes, which would settle down to a final value of $\frac{1190\times 3}{3.7}=965$ amperes. These figures indicate that great synchronizing difficulty is to be expected, especially with several machines running. Evidently all neutral currents at this time may be avoided by connecting the neutral of the incoming machines only after an adjustment of the load.

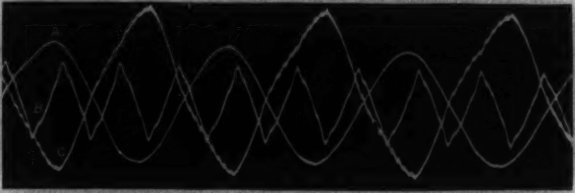

FIG. 18.—Voltage wave forms at 9,000 kw. load (non-inductive) 5000 kw., 11,000-volts., three-phase Y-connected generator
A = Line to neutral generator
B = Line to line
C = Neutral of generator to neutral of system

REMEDIES

Practice and the computations made above show beyond question that with certain types of generators parallel operation with interconnected neutrals is impracticable and dangerous to continuity of service.

The best remedy is to build machines in which no triple harmonic voltages can exist. These troublesome harmonics may be eliminated at no load by the proper shaping of the pole pieces. There are in addition, however, triple harmonics due to armature reaction which are increased by a decrease in no load neutral voltage.

The remedies possible are two; the distribution of the excitation m.m.f. sinusoidly over a uniform air gap so that the armature reaction will be without higher harmonics; or the design of the armature winding so that no triple harmonics may be generated therein. Comfort A. Adams shows in the above mentioned papers that this latter condition may be obtained by a winding distributed over 120 consecutive electrical degrees of armature space.

It is probably impossible to reduce neutral voltages and currents to zero, but there should be no trouble in reducing them to negligible magnitudes.

CONCLUSION

In conclusion then, it appears that alternators as usually built, are unsuited for parallel operation with interconnected neutrals. The difficulty is greatest during the operation of synchronizing, but may be considerable at other times unless the prime movers have uniform driving torques. However, it is perfectly feasible to build alternators that will give no such trouble. When such machines are required, it should be specified that the neutral voltages both on open and short circuit, shall not exceed 1 to 2 per cent of the corresponding fundamental coil voltages, instead of from 10 to 15 per cent, as is now frequently the case. It should further be specified that the short circuit neutral currents shall not exceed 10 to 15 per cent of the full load coil current, instead of 100 per cent as is now common.

Machines built to meet these specifications will operate with complete satisfaction with their neutrals solidly connected together.

DISCUSSION ON "PARALLEL OPERATION OF THREE-PHASE GENERATORS WITH THEIR NEUTRALS INTERCONNECTED". SAN FRANCISCO, CAL., MAY 5, 1910.

H. J. Ryan: The author of this paper defines the factors that cause undesirable currents to circulate among the common neutrals of large Y-connected alternators operated in parallel. He develops analytically the relations of those factors so that the magnitude of the circulating currents may be predetermined with a fair degree of accuracy. To be able to do this is half the battle that must be fought to reduce them to harmless proportions.

In the Interborough and similar plants, the alternator neutrals are paralleled and grounded so that an underground cable feeder in which a fault through the insulation to ground develops will be automatically disconnected before the fault grows into a complete and destructive short circuit. This mode of operation developed troublesome circulating currents among the paralleled neutrals of the alternators. The remedy finally adopted was to ground the neutral of but one alternator. in each of the two Interborough stations operating in parallel. The proportions employed in setting the feeder circuit-breakers, resistance of ground connections, etc., are such as to secure maximum effectiveness of the protection thus accorded the underground system.

This eliminates the paralleled neutrals and constitutes one remedy that has been put into practice with rather good results.

At the close of this paper the author proposes two additional remedies:

1. The distribution of each armature phase over 120 deg. fundamental, in lieu of 60 deg.

Each pair of actual or fundamental poles have as third harmonic components six small poles. These proposed broad armature coils cut such third harmonic poles in opposing pairs. Phase opposition occurs in developing the corresponding third harmonics e.m.fs. with a net result of zero for such e.m.fs., no matter to what extent the third harmonic poles may be produced by armature reaction.

2. A uniform distribution of air-gap reluctance and a polar distribution of field excitation m.m.f. so as to match the distribution of armature reaction m.m.f.

This practically implies an alternator modeled structurally much like an induction motor or generator.

These are features that the factories can very likely find a way to meet. Doubtless generators of this character should be somewhat less desirable in other respects, because they are not now found in practice. As against the compromise method now in use designated above as No. 1, is either method, No. 2 or No. 3, desired sufficiently to offset the manifest disadvantages that must exist somewhere for the reason just given? One hopes that the discussion of this paper will throw some light hereon.

The author of the paper has done the profession a real service in demonstrating that all problems which owe their origin to non-sine wave conditions may be solved by the sine-wave methods applied to the multi-frequency components of the original irregular alternating waves. The method looks complicated because of the many terms that the several frequencies introduce. Inherently it is nothing more than an extension of our common methods.

S. J. Lisberger: In paralleling the two alternators, Mr. Rhodes speaks of alternating the two; does he leave the neutral of the alternator that is to be grounded, when the two are in final parallel, open until the two are synchronized, or is it closed at the moment of synchronizing the two alternators?

G. I. Rhodes: We have little occasion to parallel two generators with their neutrals interconnected. Normally, one unit in each plant is connected to the neutral bus. When this grounded machine is to be taken out of service the neutral of a second is grounded and then that of the first cleared. This procedure allows the two machines to run for a short time with their neutrals in parallel.

When the two stations have to be synchronized the operation is performed with the neutral of each grounded. The rheostats however, limit the interchange of current to a small value.

The primary object of the ground resistance is to limit the flow of current to a grounded cable. This is the sole object where a single rheostat is used. Where a separate resistance is inserted in the neutral connection of each generator it has the added function of greatly reducing the interchange of triple harmonic currents between machines.

C. L. Cory: On the Pacific Coast we have had some experience in operating high-voltage Y-connected generators, and the resultant higher harmonic e.m.fs. There are one or two things I may add to the paper, not so much regarding the operation of the generators in the station but the results on outside circuits of grounding the neutral.

There are in the Redondo Station of the Pacific, Light & Power Company three 5000-kw., 18-000-volt, Y-connected generators directly driven by reciprocating engines and during a fifteen day test of one of the units, as well as during the regular operation of the plant, the presence of these higher harmonics was observed in a manner somewhat similar to that outlined in the New York station. I do not know exactly what was done regarding the neutral connections to the ground after the test was completed, but during the test ammeters were connected in the neutral circuit to the ground from each of the three generators. It was observed that the ground currents varied with the relative loads upon the generators.

I do not recall at this time what arrangement was made regarding the neutral connections during the synchronizing of the generators, but the three generators were operated in synchronism during the test and the plant as a whole was run in synchronism with water power and other steam driven stations many miles away.

One thing which was observed, of which you unquestionably have knowledge in the operation of such machines, was the impossibility of connecting the secondaries of the transformers in delta with their primaries connected Y since there is a current due to the e.m.f. of the higher harmonic waves which manifests itself in the delta connection of the secondary side. There is another point, and if I am wrong, Mr. Rhodes, I will be very glad to have you correct me, is that the magnitude of the current from the neutrals to the ground due to the higher harmonics, principally the third, depends directly upon the voltage of the generators.

G. I. Rhodes: Yes. The current flowing to ground on account of the electrostatic capacity of the lines is directly proportional to the voltage. The interchange of current between machines is the same proportion of full-load current irrespective of the voltage.

C. L. Cory: Therefore, if we should reduce the voltage of these generators from 18,000 volts down to 2300 volts the magnitude of the ground currents would be correspondingly reduced, which reduction of voltage, while not a complete solution, would reduce the trouble.

The principal difficulty which was found in this case was the interference with the telephone and telegraph lines wherever there was an exposure of such circuits near the high-voltage transmission lines connected with the system. Telephone lines that operated very satisfactorily before the neutral was connected with the earth were, after this connection was made at the station, practically rendered inoperative. We have here to-day, Mr. President, the engineers of the telephone company and since they have to a great extent inoperative the conditions produced by the operation of high tension transmission systems on the coast, this side of the matter should I think be given due consideration. It is apparent, as set forth in Mr. Rhode's paper, that telephone and telegraph line interference may be of considerable magnitude during the time when the generators are being started and synchronized and that the conditions would not be so severe during the normal operation of the generators, although with the changing loads on the generators serious troubles might be encountered.

In this connection it is worth remembering that very little difficulty, comparatively, has resulted from grounding the neutrals of the 60,000 volt and 100,000 volt transmission lines where the generators are operated at comparatively low voltage and the high line voltage is obtained by step-up transformers.

There is another instance in Southern California where a large steam turbine with a Y-connected high-tension generator had the neutral grounded. In this case the higher harmonics interferred seriously with the operation of the telegraph system. the telegraph and transmission lines running parallel along the right of way of the Southern Pacific Company for a number of miles.

In the general solution of the problems which have arisen and will continue to arise in connection with transmission lines and telegraph and telephone lines, there is no question but that the equations and discussions as set forth in the paper, as well as the conclusions of the author, will be of material advantage.

President Stillwell: I would ask Mr. Rhodes whether he, during his investigation, measured or approximately measured the variation.

G. I. Rhodes: No such measurements have been made.

President Stillwell: Did you form any impression as to whether the variation in angular velocity in the case of the reciprocating engine was quantitatively a serious matter as affecting the interchange of current? In other words, is there serious disadvantage, in your judgment in using a reciprocating engine as compared with a water or steam driven turbine, assuming that armatures are similarly wound?

G. I. Rhodes: The difficulty of operating the plant with the neutrals in parallel was due primarily to the variation in angular velocity of the engines; the trouble during the operation of synchronizing could have been avoided by closing the neutral afterwards. Where turbines are used there is no appreciable surging in the neutral connections.

It is possible to introduce triple harmonic current by unequal excitations, but under normal conditions these currents are negligible.

President Stillwell: The point I have in mind is, would the variation of angular velocity, in the case of a winding having two slots per phase per pole, be serious from a practical operating standpoint?

If you had *no* third harmonic would it be serious?

G. I. Rhodes: The number of slots per pole has no direct influence on the neutral current. If the alternators had been designed to be without triple harmonics under all conditions of load, the variations in angular velocity would not have been serious. It would have been possible to operate the machines with their neutrals in parallel, without any interchange of current other than that which would occur with the neutrals disconnected.

C. F. Adams: In connection with this question, I do not think the question of circulating currents in grounded neutrals has ever been an issue as far as the apparatus of the Pacific Gas and Electric Corporation has been concerned until possibly within the last few months. Many of the generators at the power stations are Y-connected, others are delta-connected. I don't think the question of the circulating current in neutrals has ever become anything of a factor. At the Oakland station the high potential transformers are of course star-connected on the 2,300-volt side. With synchronous motors of the Stanley type, running connected in the same manner with grounded neutral, there is absolutely no flow of current through the neutral that is noticeable. With the turbines floating on the line, there is no appreciable flow of current through any of the meters, but there is present a circulating current through the neutral of approximately 300 amperes. The speed of the turbines is 720 revolutions, and with practically all of the rest of the system being water-driven, this question of angular velocity would not seem to be much of a factor. I think the matter of current flow is probably due to the variation in the type of pole face used in the generators. That is my opinion and belief at the present time. Mr. Downing has made some experiments in that line, and possibly he can give us some information.

Paul Downing: We have made some tests along the lines which Mr. Adams has indicated, but have not as yet reached any definite conclusion. We have a circulating current there, which is practically constant, regardless of the load carried by the turbines. This particular turbine runs in connection with the transmission line, which is supplied with power from hydroelectric plants. A great deal of the time that particular turbine carries no load, simply floating on the line. As I say, we have not progressed quite far enough with our experiments yet to arrive at any definite conclusion.

Along this same line I would ask Mr. Rhodes if it is common practice to operate different stations in parallel on a given network, and if so, whether or not the current on the neutral of one machine in each station, or one machine, feeds in to a given network.

G. I. Rhodes: The system with which I am connected, consists of two plants operated in parallel with a single generator in each station grounded through a resistance. These resistances practically eliminate trouble from the neutral currents. There is no reason why a network having several power stations could not be operated in this manner.

E. F. Scattergood: Mr. Rhodes speaks of several machines operating in parallel and suddenly one of these machines dropping out. I would ask if that occurs with the turbines or only with the reciprocating engines, or with both?

G. I. Rhodes: There was no definite indication of why a machine would drop out suddenly. It was probably due to the valve motion on the engines. When the machines were operated in parallel with their neutrals interconnected, the surging was very irregular. At times an especially heavy surge would occur on a machine without cutting it out, but this was frequently a preliminary signal of trouble. There should be no trouble of this kind in steam-turbine or in hydraulic plants.

W. F. Lamme: I would like to ask about the regulation of the machine. I have had some experience in paralleling alternators and have noticed that where a machine would run perfectly parallel up to 400 volts, at 2000 volts you could not get satisfactory work out of it at all.

G. I. Rhodes: The inherent regulation of these generators figures out at about four and one-half per cent.

P. M. Lincoln: My judgment of the value of this paper is based entirely upon the conclusions which are mentioned in the last few paragraphs and particularly to the one conclusion which is mentioned in the first sentence of the concluding paragraph. This reads as follows:

> In conclusion then it appears that alternators as usually designed and built are not suited for parallel operation with their neutrals interconnected.

Judging from this it seems that Mr. Rhodes has attempted to demonstrate something contrary to actual facts.

I am familiar with the designs and practice of alternating-current generators as made by the company with which I am connected, and quite a considerable number of the generators made by this company has been operated on four-wire three phase systems with the neutrals of the generators solidly connected to the neutral of the system operated, thus forming the systems with interconnected neutrals such as Mr. Rhodes discusses. In no case where such practice is in use has any particular attention been paid to the design of the generators with a view of reducing any disturbances which might arise from these interconnected neutrals. In the operation of such generators as have been used with interconnected neutrals there has never been any reason for complaint on account of this connection with the single exception of the plant with which Mr. Rhodes is connected. In view of the fact, therefore, that quite a large number of plants are using this method of operation and the further fact that this method is becoming more and more popular as time goes on, I do not think that Mr. Rhodes' broad conclusion is in any sense justified.

The question of circulating currents between various generators operated in parallel is by no means a question of the generators only. The prime movers which operate these generators have a great deal more to do with the magnitude of these circulating currents than has the generator itself. In any plant where alternating current generators are paralleled, currents are bound to circulate between the various units in parallel. The magnitude of these circulating currents is dependent to a very large degree upon the uneven driving torque which is a necessary accompaniment of reciprocating engines. It is well known that the power output of any reciprocating engine is not constant at all times. It rises to a maximum at the beginning of the piston stroke when the pressure within the cylinder is nearly boiler pressure and falls to a minimum at the end of the stroke, when there is no effective pressure within the cylinder. On the other hand the power output of an electric polyphase generator into its circuit is constant, and is the same at each instant of time. The average power output of an engine is equal to the average power output of the generator plus the losses. The excess or deficiency of power in the engine cycle therefore is devoted to two things—first, the speeding up or slowing down of the flywheel which is attached to the generator, and second, a somewhat increased or decreased power output from that particular generator on account of the fact that its e.m.f. wave is forced somewhat ahead or lags somewhat behind the e.m.f. waves of the other units in circuit at the same time. This fact that the e.m.f. wave of one generator is ahead or lags behind the e.m.f. wave of the other generators in circuit at the same time is largely responsible for circulating currents. So long as the various generators are three-phase and are connected together on the outside terminals only it is impossible for triple harmonics or multiples thereof to constitute any part of the currents which circulate between the various units. This is on account of the fact that in the outside terminals of no three-phase generator is it possible for triple harmonic e.m.fs. to appear. As soon, however, as the neutrals of the various generators are interconnected the triple harmonic current can flow and under some conditions this triple harmonic current becomes a very large proportion of the total circulating current that appears between the various units. The flow of this triple harmonic current can be readily determined by placing a meter in the neutral connection between the various units in parallel. It should be borne in mind, however, that the current circulating through the windings of the generator is only one-third of the current which is thus measured as coming from the neutral of the generator. The triple harmonic current in each of the three phases of the generator windings are all in phase and thus the triple harmonic current in the neutral is three times that in the generator winding itself. For instance a triple harmonic of 75 per cent of full load measured in the neutral wire means that only 25 per cent of full load current is circulating through the generator windings. The heating effect of such a 25 per cent triple harmonic superposed upon full load fundamental current would increase the total effect only by 3 per cent. It is quite easy therefore to obtain from measurements made in the neutrals of three-phase generators in parallel an exaggerated idea of the importance of circulating triple harmonic current that may be found between these various units. I do not know of any case where so much as 75 per cent of full load current has been found as a normal condition but I cite an example having an excessive triple harmonic current so as to show how unimportant a part such a circulating current really plays so far as heating of the armature winding is concerned.

Another condition has a very important effect upon this circulating current and that is the amount of armature reaction.

In general the greater the armature reaction (that is the poorer a given machine regulates) the less will be the circulating currents which will be caused by a given departure of the prime mover from uniform rotation. The generators of the Interborough Rapid Transit Company, with which Mr. Rhodes is familiar, have very close regulation. Their short-circuit ratio is over three. In other words, this simply means that a given amount of armature current has less influence over the field than the same amount of armature current would have in a generator whose short circuit ratio is, say, two. Conclusions, therefore, which are reached from a study of machines whose short-circuit ratio is three or more, such as the Interborough machines, do not necessarily hold when the short-circuit ratio is considerably less as is the usual practice in more modern machines.

With recent type machines there may be even a considerable departure from uniform rotation in the prime movers and still the circulating current with interconnected neutrals will not reach a value sufficient to cause the slightest inconvenience. A case in point is the experience of a lighting company in Pittsburg. This company operates a number of 4000-volt generators in parallel with neutrals solidly interconnected. The voltage from the neutral to each outside is about 2200 and all of the lighting by this company is done from neutral to outside. These particular machines are driven by gas engines and the plant has been in operation for a number of years. It is well known that the gas engine has about as great a departure from uniform rotation as any prime mover, but in the case cited above there has not been the slightest disturbance of any kind and neither has there been any question concerning the desirability or advisability of operating their machines in this manner. Quite a number of other plants are using the four-wire, three-phase system of distribution and are connecting the neutrals of their generators direct to the neutral of their systems. This method of operation is becoming more and more favored as time goes on and so far as ordinary generator design is concerned there is nothing to prevent it. This has been proven by the experience of quite a large number of plants.

It is quite evident therefore that experience has proven quite the contrary of the broad conclusions laid down in Mr. Rhodes' paper. It is both unnecessary and inadvisable to follow out the suggestion of making more or less freak generators such as Mr. Rhodes suggests for the overcoming of a difficulty which in actual practice does not exist.

G. I. Rhodes: I believe I have answered most of the questions that have been asked of me, so I will say a few words with respect to Mr. Lincoln's remarks. I also know of a plant of large size operating with neutrals solidly connected together, that did not have any trouble. Some months ago an attempt was made to get a manufacturing company to build generators which it would guarantee as to operation with the neutrals in parallel. No such guarantee could be obtained. It is hard to say why there has been no trouble with the plants Mr. Lincoln mentioned, but if I knew more about the details of the machines, I might be able to explain it.

In response to what Mr. Cory has said about telephone lines, I might bring up an instance of some difficulties experienced with triple frequency current. I have in mind some special tests we made on one of our small turbines, and during this test we had occasion to put in circuit some 35 miles of underground cable operating at 11,000 volts between phases. There was a triple-frequency component of 500 volts in the potential to ground. The neutral current was considerably larger than the line current. The oscillograph record taken during that test was published by Mr. H. G. Stott two years ago. TRANSACTIONS A. I. E. E., Vol. XXVII Part II, page 1536.

C. A. Adams (by letter): As this subject is one in which the writer is greatly interested, he cannot refrain from expressing his admiration for the author's courage in attacking and skill in carrying out even a roughly quantitative solution of this problem. The approximations are necessarily rather gross, but the results should be, and in fact seem to be, close enough to be of great practical value.

There is much food for thought and discussion in connection with the method of analysis and the approximations involved, but as most readers of the TRANSACTIONS are more interested in the remedies for the difficulty, I will stop here to question only one of the author's assumptions, namely that the effective third harmonic reactance at the instant of short circuit " is not over 20 per cent of the (third harmonic) leakage reactance ", if the slot leakage were entirely neglected the coil end leakage alone would ordinarily amount to more than 20 per cent of the total, especially in a 25-cycle turbo-alternator.

Coming now to the remedies, the author has neglected entirely the consideration of fractional pitch windings,[1] although his suggestion of a 120 degree belt span is in some respects equivalent to a two-thirds pitch. A two-thirds pitch with a 60 degree belt would eliminate the third harmonic entirely under all conditions of load, and would save considerable copper and overall length of machine, as compared with the 120 degree belt at full pitch.

Other things being equal the two-thirds pitch winding would require about 15 per cent more slot copper, but a little less coil end copper than the full pitch winding; but as the coil end copper at full pitch is frequently more than 50 per cent of the total, the increase in total armature copper would be only 6 or 7 per cent, which could be neutralized by a slight increase in peripheral velocity. The saving as compared with the 120 degree belt full pitch winding would be 8 or 9 per cent.

It should be noted that the reducing effect of the two-thirds pitch upon other than the triple harmonics is the same as upon the fundamental, so that the relative magnitudes of these other harmonics remain the same. But the belt differential factor reduces each of these, say the nth harmonic, to 1-nth of its value in the flux distribution curve. Thus with any reasonable shaping of the pole face, the 5th, 7th, 11th, 13th, etc., harmonics will be reduced to comparatively small values. However, if it were important to reduce them still farther, it could be done by a double winding in two layers connected in series, each of the two layers giving the same e.m.f. wave-shape as the original winding and the two layers displaced in phase enough to largely eliminate the more important harmonics. The best phase displacement for this purpose is 30 degrees in a three phase machine, see Fig. 9 of the writer's article on "Alternator Wave Shape" referred to above.

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[1] " E.m.f. Wave Shape in Alternators ", TRANSACTIONS A.I.E.E., Vol. 28 (1909) p. 802; " Fractional Pitch Winding for Induction Motors ", TRANSACTIONS A.I.E.E., Vol. 26 (1907), p. 1485.

This last suggestion would involve considerable additional insulation and complication in winding, and should not be necessary with any reasonably good flux distribution curve.

The author's second suggestion for a remedy, namely a uniform gap and distributed field winding, seems to be quite feasible, although it would be better when combined with a moderate pitch reduction. It should not be difficult with distributed field windings, such as now in considerable use, to obtain a flux distribution of trapezoidal form in which the third harmonic is negligibly small, but with a moderate fifth harmonic. The latter could then be eliminated from the e.m.f. by a coil pitch of 80 per cent or thereabouts.

S. B. Charters Jr., W. A. Hillebrand (by letter): It may be of interest to know that the phenomena described by Mr. Rhodes can be duplicated under laboratory conditions.

Two identical 7½-kw., three-phase, Y-connected alternators, 380 volts per phase, were operated in parallel on a non-inductive load, with the following results:

Line E.	Load I.	Current delivered by one alternator.		Neutral current.	Neutral Potential.
		Neutral, out or open.	Neutral, in or closed.		
Load. .. 349.	5.4	3.15	3.35	2.7	2.1
No load 379.	0	3.75	4.1	4.1	3.1

Excitation was adjusted for minimum cross currents between the two machines.

Armature impedance for each leg of the Y-connection, 2.6 ohms at 60 cycles.

$$3 \times 2.6 = 7.8 \text{ ohms, at 180 cycles.}$$

Synchronous reactance per phase of each alternator, 3.5 ohms.

Assuming a synchronous reactance to the third harmonic of 2/9 that to the fundamental, as given by Mr. Rhodes, the neutral current for each of the above cases is computed as follows, dividing the measured neutral potential by the impedance of two phases in series.

Load

$$I_n = 3\times \frac{2.1}{2\times 7.8+2\times 2/9\times 3.5} = 0.367 \text{ amp.}$$

No load

$$I_n = 3\times \frac{3.1}{2\times 7.8+2\times 2/9\times 3.5} = 0.542$$

Ratio, observed to computed neutral currents,

Load $$\frac{2.7}{0.367} = 7.36$$

No load $$\frac{4.1}{0.542} = 7.57$$

The discrepancy between observed and computed values for the neutral current seems to be due to an amplification of the third harmonic e.m.f. introduced by the third harmonic itself. This was checked by measuring the circulating current in one of the machines operating no load, delta connected, as follows:

Line E	3d Harmonic E with delta open.	3d Harmonic circulating current.
220	17.8	5.0

By computation the third harmonic should be

$$I_3 = \frac{17.8}{3\times 7.8+3\times 2/9\times 3.5} = 0.693$$

Ratio of observed to computed current,

$$\frac{5}{0.693} = 7.22$$

This is a reasonable agreement with the previous ratios 7.36 and 7.57.

The oscillograph showed that the current circulating in the delta was practically a pure third harmonic.

G. I. Rhodes: The apparent discrepancy between calculated and observed neutral currents as given by Messrs. Charters and Hillebrand may possibly be explained as follows: The value of the reactance to triple harmonic current is given in the paper as the sum of three times the leakage reactance plus 2/9 of the reaction reactance. This latter quantity is defined as the difference between the synchronous and the leakage reactances. The figure given for leakage reactance is abnormally high and on that account is open to some question. It is probable that there was a misunderstanding as to the definitions of the reactances to be used in calculating neutral current.

Mr. Lincoln's adverse criticism of the paper deserves attention. His chief objection appears to be based solely on the wording of the conclusion, without any reference to the subject matter leading up to it. His discussion seeks to establish the fact that alternators as usually designed and built are suitable for operation with interconnected neutrals, without special consideration to design.

The fact that some machines have proved incapable of operation with paralleled neutrals indicates beyond a doubt that design has a great deal to do with it, and the cause of this trouble should be investigated rigidly so that it may be avoided in future installations. This paper has investigated the cause and suggested a remedy.

Mr. Lincoln offers in support of his criticism, the satisfactory operation of certain plants with solidly interconnected neutrals' He gives absolutely no details to indicate whether or not these generators embodied any elements of design tending to reduce neutral currents, or as to their size, number, or conditions of operation. He specifically mentions the generators which have caused trouble, as special, on account of their low armature reaction.

The writer has investigated the only plant mentioned with sufficient detail to afford identification. This plant consists of two 200-kw. 4000-volt, three-phase, Y-connected, gas-engine-driven generators. They are designed with large armature reaction and large leakage reactance, to limit interchange of current. The neutrals are solidly connected together as are also the lines as far as automatic switches are concerned.

What is satisfactory operation?

At the time the writer was in the plant there were occasional surges between the generators sufficient to cause the wattmeter on one to fall to zero, and that on the other to rise to double the load with violent oscillations. The engineers seemed not in the least worried. It was evidently not an uncommon occurrence. Such conditions which were " satisfactory " in this 400-kw. plant would have been disastrous in a plant of 40,000 kw.

This small plant consisted of but two units. It has been found quite possible to operate two units in the plants with which the writer is connected. It was sometimes possible to operate even three, but it was absolutely impossible to operate more than this number. If this gas-engine plant had consisted of eight to ten units as is frequently the case in larger systems, it is probable that there would have been trouble.

Mr. Lincoln makes a statement as to the unimportance of the heating effect of the neutral current. He states that a 75 per cent current corresponds to a 25 per cent triple harmonic coil current. He states the increased heating effect is 3 per cent. This figure should be 6 per cent, for the increased loss is proportional to the square of the current value of non-fundamental frequency. Thus, the heating with 75 per cent neutral current is $1.00^2 + 0.25^2 = 1.063$. The extreme figure given by Mr. Lincoln for neutral current is very much too small. The writer has knowledge of a case in which the current was several times full load. It is thus evident that the heating effect of neutral current is not always negligible.

Mr. Lincoln's reference to the low armature reaction of the machines which have proved incapable of satisfactory operation with interconnected neutrals indicates his belief that this low reaction was responsible for the trouble.

If he had studied the paper instead of the conclusion he would have observed the following:

1. Neutral potential is directly proportional to armature reaction.

2. Neutral current is independent of armature reaction.

3. Neutral current is in the inverse ratio to leakage reactance.

That is, the small reaction had nothing whatever to do with the interchange of neutral current which proved dangerous.

Mr. Lincoln, after attempting to demonstrate the non-existence of a condition proved in the paper without pointing out a flaw affecting the value of the work, criticises the proposed remedies as "freak." That is, a winding occupying 120 consecutive electrical degrees per phase or a smooth rotor with distributed field winding is a "freak." Every two-thirds pitch winding having a belt span of 60 degrees fulfills the first specification. This type of winding is by no means rare, as may be discovered by an inspection of some of the armatures in the shops of the large manufactuing companies. It is frequently used to obtain the best copper economy under certain conditions of design. It is by no means improbable that some of Mr. Lincoln's satisfactory generators which have given no cause for complaint contain such windings, although those examined by the writer had full pitch coils. Many turbo-alternators are now built with uniform air gaps and field windings distributed to give a good wave form. It is safe to say that there are in existence alternators in which the triple harmonic potentials or currents generated are of very small value. They have never before been branded as "freak."

The conclusion given in the paper still stands. It is unsafe to depend on satisfactory operation of alternators with interconnected neutrals unless triple harmonics are eliminated by proper design. Such machines are entirely practicable and should be specified whenever paralleling of the neutrals is required.

Ralph D. Mershon (by letter): The papers by G. I. Rhodes and J. J. Frank, are closely related. Their correspondence becomes evident when we consider some of the consequences of operating generators in parallel with their neutrals interconnected. With such connection it is possible to safely and effectively operate all transforming equipment with both windings connected in Y and with all neutrals interconnected. Under these conditions, the dangerous third harmonic voltage, of which Mr. Frank's paper treats, disappears, and might therefore be ignored in general engineering practice, except where connections other than Y become necessary.

But the elimination of the third harmonic voltage, due to the exigencies of iron magnetization, is not the only advantage of Y connection. There is another advantage, though the importance of it in transmission work does not seem to be generally realized.

If a transmission system be supplied from generators operating with their neutrals connected to a neutral busbar, and with all transformer windings connected in Y, the system is simpler and more flexible than one in which any delta connections are employed. We may say that it is a system made up of three independent, or nearly independent, single phase circuits 120 deg. apart. This is not true of a three phase circuit in which the three phases are inter-related through delta-Y or delta-delta connections.

Let us consider a transmission system on which the generators are run with a neutral busbar and of which the step-up transformers are run in Y on both high and low voltage sides. Then each transformer will require only two switches to cut it clear of all voltage, one in one high voltage lead and one in one low voltage lead. Each of the other two leads will be connected to a neutral bus which may be grounded. This latter connection may be made by any suitable connector, since it will seldom have to be distrubed and will be perfectly safe to handle at all times. On the other hand, with transformers in delta-Y three switches (two for one winding and one for the other) are required, and with them in delta-delta four (two for each winding) are necessary to perform the same service.

Again, a spare step-up transformer will, for delta-Y connection, require nine switches, and for delta-delta connection twelve switches, to enable its use to replace any of the operating transformers. With Y-Y connection, only six switches are necessary for the same service.

The same simplification applies to the step-down transformers, if the high voltage neutral of both step-up and step-down transformers be dead grounded or grounded through a resistance of relatively moderate value. If either of them be ungrounded or grounded through a high resistance, the step-down transformers must be connected in delta on at least one set of windings in order to avoid the possibility of collapse of the voltage triangle.

There have been some remarks in the previously published discussion of Mr. Rhodes' paper to the effect that such a paper has no particular bearing on present practice, since generators are already in practice operated with their neutrals interconnected. These remarks give the impression that satisfactory operation under such conditions can be readily attained, and that there is no reason why it should not be a usual thing without any particular precautions in design and operation of the generators. This is quite contrary to my experience. When endeavoring to obtain generators for operation on a neutral busbar I have found that the manufacturers refused to extend the usual guarantees to operation in this manner. I am glad to know that generators for such operation can now be readily obtained, and hope that when next the demand for them arises I shall find them obtainable without the exception that has been imposed heretofore.

These two papers strike me as valuable and important ones. I think they will hereafter furnish a starting point for the explication of many of the phenomena of alternating current transmission systems.

H. Y. Hall (by letter): There are three schemes for the operation of grounded neutral systems, as exemplified by the practice of the Manhattan Railway Co., New York Central Railway and Southern Pacific Co.

At the Manhattan Railway plant, see Fig. 1, only one machine at a time is grounded. The advantage of the scheme is that the resistance between neutral and ground does not vary with the number of generators in operation, but is fixed and practically constant, thus allowing a sufficient current to flow to the ground to trip the relay in case a feeder becomes grounded. The disadvantage of this scheme is that during the time consumed in transferring the ground connection from one generator to another the system is ungrounded. This scheme has proven satisfactory during six years of service.

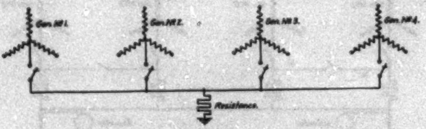

FIG. 1.—Manhattan Railway Co. practice

As will be seen from Fig. 2 the scheme used by the Southern Pacific Co., at its Fruitvale plant is the same as that used by the Manhattan Railway Co., except the use of single-pole double-throw switches instead of single-pole, single-throw switches for the neutrals and the sectioning of the neutral bus. The practice will be to run with all neutral switches in the down position, except that for the grounded machine which will be in the up position. When it is desired to shift the neutral connection, the switch on the generator to be grounded is thrown up, after which the switch for the generator to be disconnected from ground is thrown to the down position. the system would be ungrounded during only the time it takes to throw a switch from the up to the down position. The neutral resistance is a grid type rheostat having a resistance of 13 ohms and capable of dissipating 6000 kw.

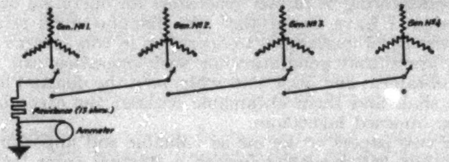

FIG. 2.—Southern Pacific Company practice

for 30 seconds without injurious heating. With a dead ground on one phase of a feeder, this resistance would limit the current to 500 to 600 amperes which is sufficient to operate the automatics on the feeders; there are no automatic devices on the generators.

At the N. Y. C. power stations, see Fig. 3, it would be safe to operate with the neutral switches closed on all four machines, if the two interconnecting switches were open, as there would be very little current flowing in the neutrals. It is not advisable

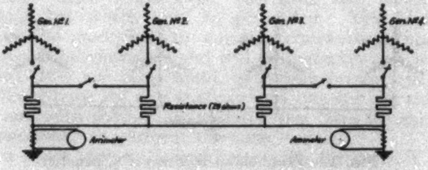

FIG. 3.—N. Y. C. & H. R. R. R. practice

to operate with all neutral switches closed as there would be only five ohms resistance between neutral and ground, which would allow too much current to flow, in case of a ground on one leg of a feeder. Two sets of resistances should be kept connected in whether one or all generators are being operated.

In connection with the installation and operation of grounded neutral systems, another point to be borne in mind is the method of connection of potential transformers. If star connected potential transformers are to be used they should be connected to the neutrals of the machine, instead of to the neutral bus or the ground bus, for the neutral connection. If they are connected to the ground or neutral bus, whenever the system is running ungrounded the potential transformer voltages will be greatly unbalanced due to the difference in the loading of the potential transformers. At the Port Morris plant of the New York Central there have been potential transformer burn-outs, due to 50 per cent over-voltage on potential transformers. The system at the time was not grounded as the operator forgot to put in the neutral switch on the machine in service. For feeders, potential transformers should be connected between phases and not to the neutral or ground.

A paper presented at the 248th meeting of the American Institute of Electrical Engineers, San Francisco, Cal., May 6, 1910.

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OBSERVATION OF HARMONICS IN CURRENT AND IN VOLTAGE WAVE SHAPES OF TRANSFORMERS

BY JOHN J. FRANK

INTRODUCTION

Ever since Professor Ryan presented his famous paper on "Transformers" before the Institute, in which attention was called to the lack of symmetry between curves of instantaneous values of current and potential applied to the transformer, numerous writers have discussed the subject from various view points.

One writer on the subject, Mr. Charles K. Huguet, draws the conclusion that the distortion is due entirely to the variations in the permeability of the iron core since hysteresis is essentially unsymmetrical with respect to the magnetization.

Dr. Bedell and Mr. Elbert C. Tuttle, in a more recent paper, present the subject from a purely theoretical view point. In their discussion, they show how complex current waves may be formed by the combination with a fundamental of triple harmonic wave shapes of different amplitude and phase relation. The significance of the resultant wave distortion and of the various hysteresis loops plotted are fully discussed and the following conclusions drawn:

1. When a sinusoidal electromotive force is applied to a coil of wire embracing iron, an alternating current will flow distorted by the presence of a third harmonic.

2. This harmonic is in advance of the fundamental by an angle ψ, which is greater than 30 deg. and less than 180 deg.

3. Considering the maximum of the fundamental as unity, the maximum of this harmonic cannot exceed a definite value of about 0.192 for $\psi = 30$ deg. and 0.333 for $\psi = 180$ deg. (See following table).

LIMITING VALUES OF β AND ψ FOR VARIOUS VALUES OF ϕ

ϕ	β	ψ	ϕ	β	ψ
0°	0.111	0°	40° 6′	0.211	29° 34′
	0.112	5° 41′	45° 14′	0.220	29° 6′
	0.113	7° 59′	46° 34′	0.222	27° 43′
	0.116	11° 8′	57° 44′	0.240	27° 28′
1° 17′	0.120	16° 20′	60° 42′	0.244	27° 1′
1° 45′	0.122	16° 54′	71° 44′	0.260	25° 8′
4° 48′	0.133	22° 30′	76° 48′	0.267	24° 9′
6° 55′	0.140	24° 28′	87° 47′	0.280	21° 56′
8° 34′	0.144	25° 35′	95° 54′	0.289	20° 12′
12° 52′	0.156	27° 40′	107° 16′	0.300	18° 4′
14° 15′	0.160	28° 15′	120° 40′	0.311	14° 34′
17° 37′	0.167	28° 57′	134° 4′	0.320	11° 22′
22° 44′	0.178	29° 41′	143° 35′	0.322	10° 23′
23° 47′	0.180	29° 47′	157° 18′	0.330	5° 43′
30° 39′	0.192	30° 00′	180°	0.333	0°
33° 59′	0.200	29° 56′			

DATA RELATIVE TO COMPLEX CURVES

ϕ	β	α	ψ	I	I′
0°	0.111	0°	0°	1.006	0.8890
2°	0.122	16° 54′	17°	1.007	0.8832
5°	0.135	22° 48′	23°	1.009	0.8833
20°	0.172	29°	29° 30′	1.015	0.9250
30°	0.193	29° 33′	30°	1.019	0.9624
45°	0.220	28° 38′	29° 22′	1.024	0.9868
90°	0.283	19° 36′	20° 30′	1.039	1.1850
135°	0.321	10° 12′	10° 45′	1.050	1.2950
180°	0.333	0°	0°	1.053	1.3330

ϕ is the phase relation of the third harmonic to the fundamental at the origin.
β is the ratio of the maximum ordinates of the fundamental and third harmonic (critical value).
ϕ is the phase difference between the maxima of the distorted and fundamental curves.
$90 - \phi$ is lag of fundamental component of current behind e.m.f.
$90 - \alpha$ is lag of equivalent sine current behind e.m.f.
I and I′ are the maxima of the equivalent sine curve and distorted curve, respectively, the maximum value of the fundamental being unity.

4. The angle of hysteretic advance due to the third harmonic cannot exceed 30 degs.

To these may be added also the following conclusions:

5. That if a sinusoidal electromotive force is impressed upon a coil, the magnetic flux threading the coil will likewise be

sinusoidal, and in phase 90 deg. behind the electromotive force, whether the coil embraces iron or not.

6. That the maximum of the current wave must coincide with the maximum of the flux. If the coil embraces iron, the maximum flux coincides with the maximum of the complex wave; if the coil does not embrace iron, the flux coincides with the sinusoidal current wave.

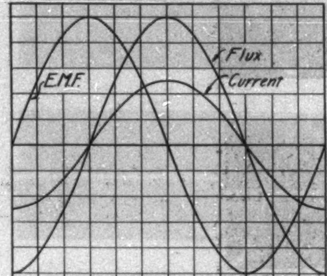


Fig. 1.—Phase relation of current, voltage and flux in a coil not encircling iron

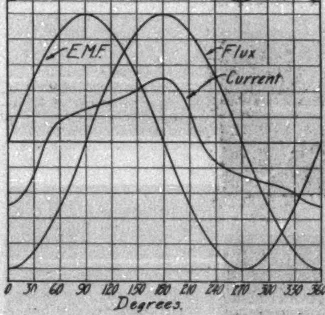


Fig. 1A.—Phase relation of current, voltage and flux in a coil encircling iron

The first four conclusions are drawn from figures given in the preceding tables taken from the paper referred to.

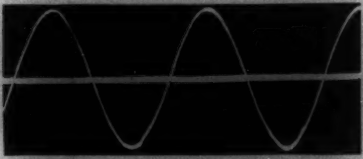
Conclusions 5 and 6 are illustrated in Fig. 1, "Phase relation of current, voltage and flux in a coil not encircling iron", and in Fig. 1 A, "Phase relation of current, voltage and flux in a coil encircling iron."

From the writer's experience, he was led to believe that the value of the third harmonic was not limited to the figures given

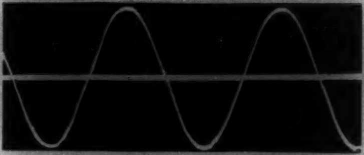
SHEET I.

Oscillograms observed on three single-phase 60-cycle, 150-kw., 4150 volt, Y-connected primary, 480-volt secondary transformers, installed in substation No. 34 of the Rochester Railway and Light Company, Rochester, N. Y.

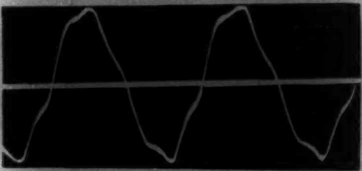
Neutral Isolated—Delta Closed



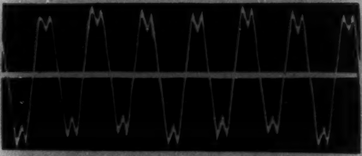
Curve No. 1
Potential, line to line, 4293 volts.



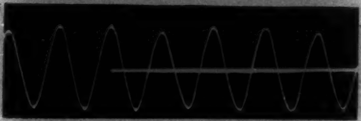
Curve No. 2
Potential across one transformer (*i.e.*, line to neutral), 2422 volts.



Curve No. 3
Current in line (*i.e.*, in transformer), 1.2 amperes.



Curve No. 4
Potential across isolated neutral (*i.e.*, neutral to ground), 125 volts

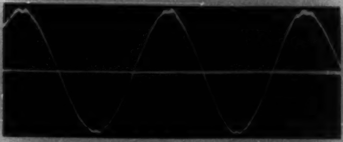


Curve No. 5
Current in closed secondary delta, 2.35 amperes.

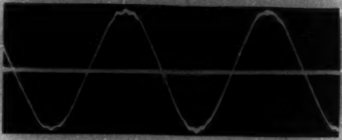
SHEET 2

Oscillograms observed on three single-phase, 60-cycle, 185-kw., 4150-volt Y-connected primary, 480-volt secondary transformers, installed in substation No. 34 of the Rochester Railway & Light Co., Rochester, N. Y.

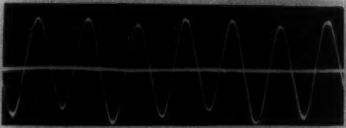
Neutral Connected—Delta Closed



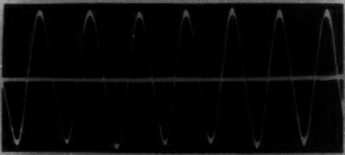
CURVE No. 6
Potential, line to line, 4342 volts.



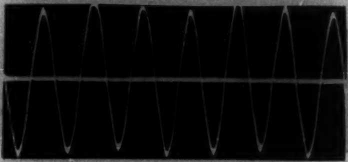
CURVE No. 7
Potential across one transformer, 2540 volts.



CURVE No. 8
Current in line, 39.5 amperes.



CURVE No. 9
Current in connected neutral, 122 amperes.

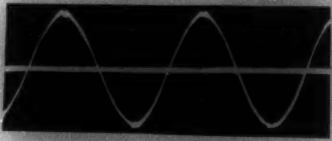


CURVE No. 10
Current in closed secondary delta, 180 amperes.

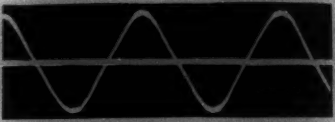
SHEET 3

Oscillograms observed in three single-phase, 60-cycle, 185-kw., 4150-volt Y-connected primary, 480-volt secondary transformers, installed in substation No. 34 of the Rochester Railway & Light Co., Rochester, N. Y

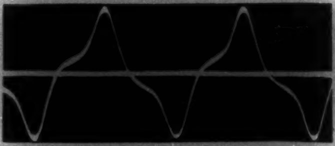
Neutral Connected—Delta Open



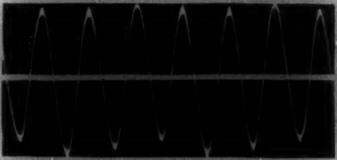
Curve No. 11
Potential, line to line, 4233 volts.



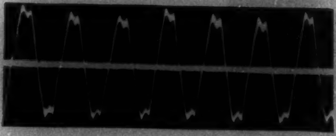
Curve No. 12
Potential across one transformer, 2453 volts



Curve No. 13
Current in line, 1.65 amperes.



Curve No. 14
Current in connected neutral, 1.45 amperes.

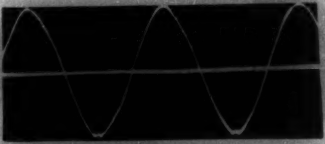


Curve No. 15
Potential across open secondary delta, 73 volts

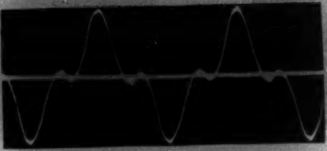
SHEET 4

Oscillograms observed on three-single phase, 60-cycle, 185-kw., 4150-volt Y-connected primary, 480-volt secondary transformers, installed in substation No. 34 of the Rochester Railway & Light Co., Rochester, N. Y.

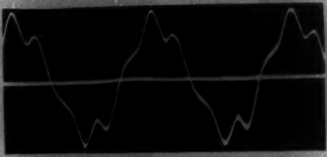
Neutral Isolated—Delta Open



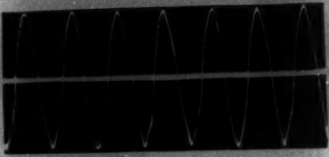
CURVE No. 16
Potential, line to line, 4250 volts.



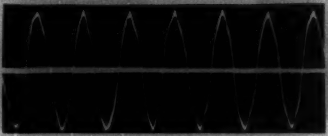
CURVE No. 17
Potential across one transformer, 2705 volts.



CURVE No. 18
Current in line, 1.1 ampere.



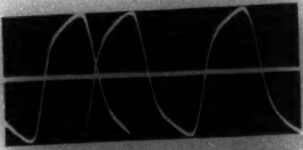
CURVE No. 19
Potential across isolated neutral, 1041 volts.



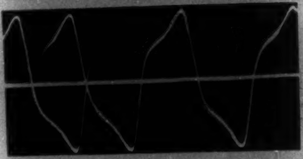
CURVE No. 20
Potential across open secondary delta, 720 volts.

SHEET 5

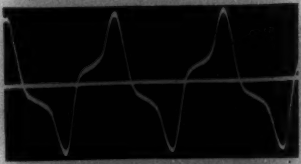
Oscillograms taken on one single-phase, core-type, 25-cycle, 185-kw. 33,000-volt primary, 430-volt secondary transformer, connected single-phase.



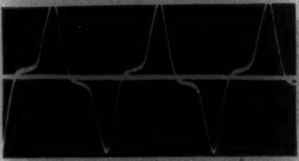
Curve No. 21
Current at 22.6 kilolines. 3.48 amperes.



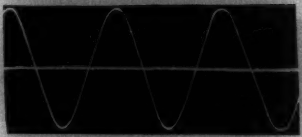
Curve No. 22
Current at 45.2 kilolines, 5.49 amperes.



Curve No. 23
Current at 67.9 kololines, 12.5 amperes.



Curve No. 24
Current at 90.5 kilolines, 35.8 amperes.

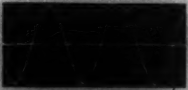


Curve No. 26
Potential at 90.5 kilolines 430 volts.

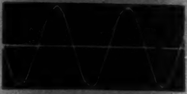
SHEET 6

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt Y-connected primary, 460-volt delta-connected secondary transformer. Density, 106.4 kilolines.

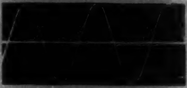
Isolated Neutral—Closed Delta



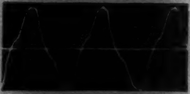
Curve No. 28
Potential, line to line, 2875 volts.



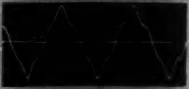
Curve No. 29
Potential across leg 1, (*i.e.*, line 1 to neutral) 1650 volts.



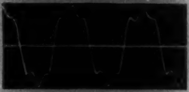
Curve No. 30
Potential across leg 2, 1650 volts.



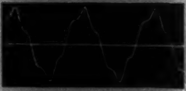
Curve No. 31
Potential across leg 3, 1650 volts.



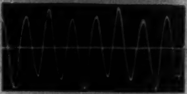
Curve No. 32
Current in line 1 3.36 amperes.



Curve No. 33
Current in line 2, 2.76 amperes.



Curve No. 34
Current in line 3, 3.0 amperes.

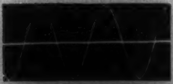


Curve No. 35
Current in closed secondary delta, 2.93 amperes.

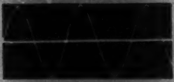
SHEET 7

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt Y-connected primary, 460-volt delta-connected secondary transformer. Density, 106.4 kilolines.

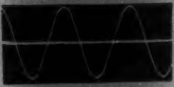
Connected Neutral—Closed Delta



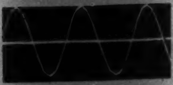
Curve No. 36
Potential line to line, 2875 volts.



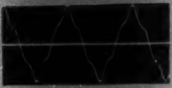
Curve No. 37
Potential across leg 1, 1652.5 volts. (42.55 kilolines, 662 volts.)



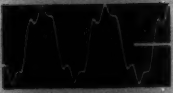
Curve No. 38
Potential across leg 2, 1652.5 volts.



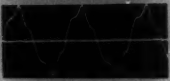
Curve No. 39
Potential across leg 3, 1652.5 volts.



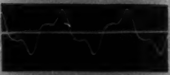
Curve No. 40
Current in line 1, 3.16 amperes.



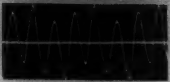
Curve No. 41
Current in line 2, 2.56 amperes.



Curve No. 42
Current in line 3, 3.26 amperes.



Curve No. 43
Current in connected neutral, 0.7 amperes.

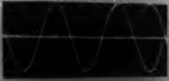


Curve No. 44
Current in closed secondary delta, 3.0 amperes

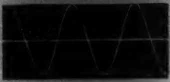
SHEET 8

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt Y-connected primary, 460-volt delta-connected secondary transformer. Density, 106.4 kilolines.

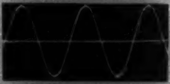
Connected Neutral—Open Delta



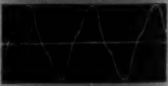
Curve No. 45
Potential, line to line, 2875 volts.



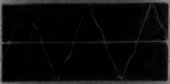
Curve No. 46
Potential across leg 1, 1652.5 volts.



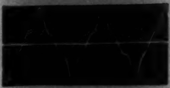
Curve No. 47
Potential across leg 2, 1652.5 volts.



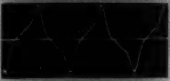
Curve No. 48
Potential across leg 3, 1652.5 volts.



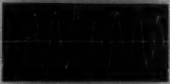
Curve No. 49
Current in line 1, 2.96 amperes.



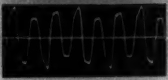
Curve No. 50
Current in line 2, 2.76 amperes.



Curve No. 51
Current in line 3, 3.16 amperes.



Curve No. 52
Current in connected neutral, 3.25 amperes.

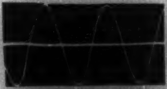


Curve No. 53
Potential across open secondary delta, 4 volts.

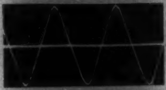
SHEET 9

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt Y-connected primary, 460-volt delta-connected secondary transformer. Density, 106.4 kilolines.

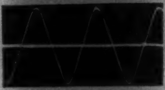
Isolated Neutral—Open Delta



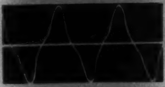
Curve No. 54
Potential, line to line, 2875 volts.



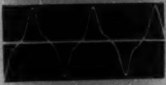
Curve No. 55
Potential across leg 1, 1655 volts.



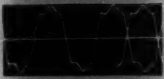
Curve No. 56
Potential across leg 2, 1655 volts.



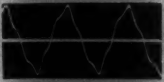
Curve No. 57
Potential across leg 3, 1655 volts.



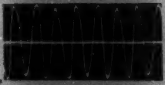
Curve No. 58
Current in line 1, 3.32 amperes.



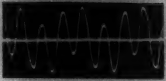
Curve No. 59
Current in line 2, 2.64 amperes.



Curve No. 60
Current in line 3, 2.94 amperes.



Curve No. 61
Potential across isolated neutral, 135 volts.

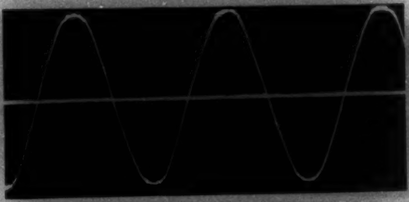


Curve No. 62
Potential across open secondary delta, 150 volts.

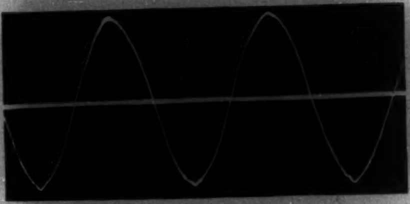
SHEET 10

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt Y-connected secondary transformers.

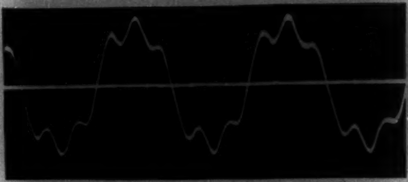
Isolated Neutral—Closed Delta



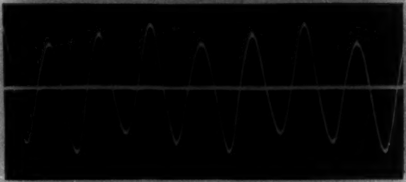
Curve No. 63
Potential line to line, 795 volts.



Curve No. 64
Potential across one transformer (*i.e.*, line to neutral), 462.5 volts.



Curve No. 65
Current in line (*i.e.*, in transformer), 5.81 amperes.

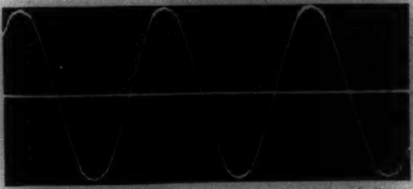


Curve No. 66
Current in closed primary delta, 0.63 ampere.

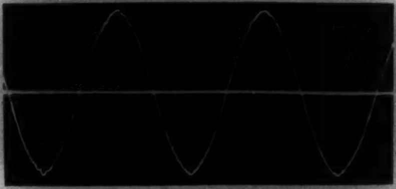
SHEET 11

Oscillograms taken on three single-phase core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt Y-connected secondary transformers.

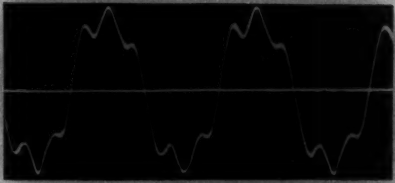
Connected Neutral—Closed Delta



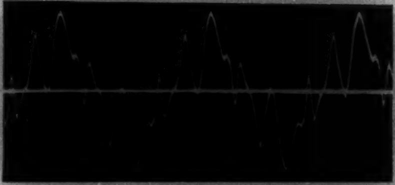
CURVE No. 67
Potential line to line, 795 volts.



CURVE No. 68
Potential across one transformer, 462.5 volts.



CURVE No. 69
Current in line, 3.88 amperes.

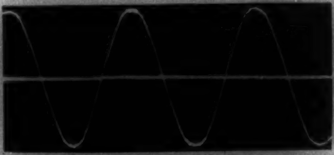


CURVE No. 70
Current in connected neutral, 0.76 ampere.

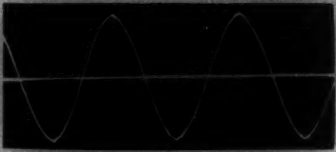
SHEET 12

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt Y-connected secondary transformers.

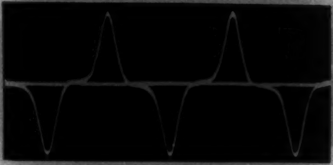
Connected Neutral—Open Delta



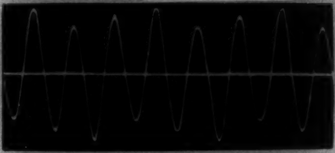
Curve No. 71
Potential line to line, 795 volts.



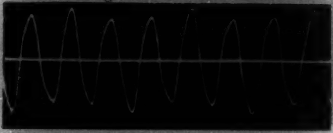
Curve No. 72
Potential across one transformer, 462.5 volts.



Curve No. 73
Current in line, 5.94 amperes.



Curve No. 74
Current in connected neutral, 9.45 amperes.

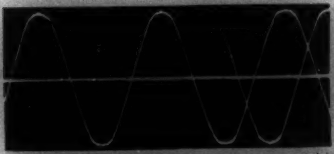


Curve No. 75
Potential across open primary delta, 24.5 volts.

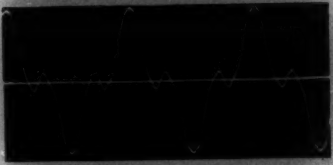
SHEET 13

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw, 2300-volt delta-connected primary, 460-volt Y-connected secondary transformers.

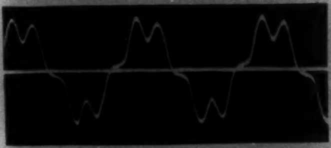
Isolated Neutral—Open Delta



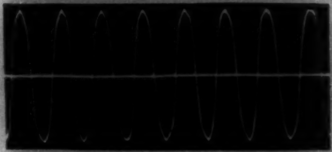
Curve No. 76
Potential line to line, 795 volts.



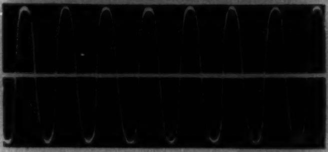
Curve No. 77
Potential across one transformer, 525 volts.



Curve No. 78
Current in line, 3.37 amperes.



Curve No. 79
Potential to isolated neutral, 257 volts.

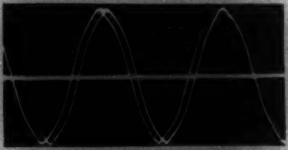


Curve No. 80
Potential across open primary delta, 3780 volts.

SHEET 14

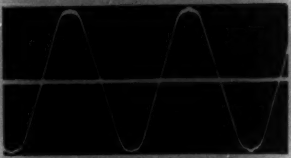
Oscillograms taken on one three-phase, shell-type, 60-cycle, 330-kw., 13,200-volt delta-connected primary, 430-volt Y-connected secondary transformer.

Isolated Neutral—Closed Delta



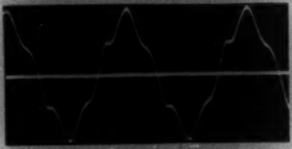
Curve No. 81

Potential, line to line, 745 volts.



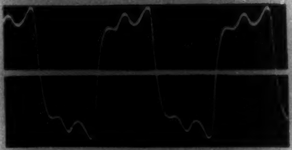
Curve No. 82

Potential across one leg (*i.e* line to neutral), 430 volts.



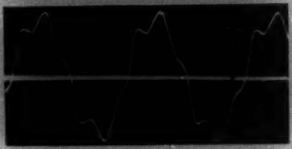
Curve No. 83

Current in line 1, 58.8 amperes.



Curve No. 84

Current in line 2, 44.6 amperes.



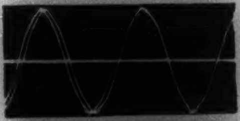
Curve No. 85

Current in line 3, 57.8 amperes.

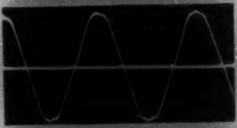
SHEET 15

Oscillograms taken on one three-phase, shell-type, 60-cycle, 330-kw., 13,200-volt delta-connected primary, 430-volt Y-connected secondary transformer.

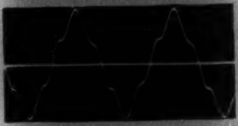
Connected Neutral—Closed Delta



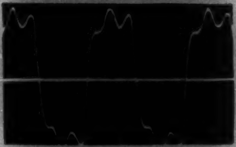
Curve No. 86
Potential, line to line, 745 volts.



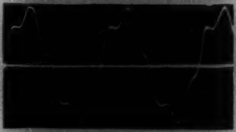
Curve No. 87
Potential across one leg, 430 volts.



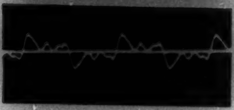
Curve No. 88
Current in line 1, 60 amperes.



Curve No. 89
Current in line 2, 45.6 amperes.



Curve No. 90
Current in line 3, 57.8 amperes.

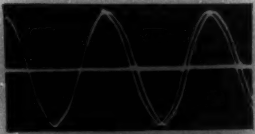


Curve No. 91
Current in connected neutral, 3.5 amperes.

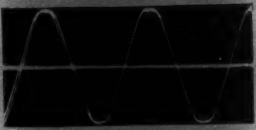
SHEET 16

Oscillograms taken on one three-phase, shell-type, 60-cycle, 330-kw., 13,200-volt delta-connected primary, 430-volt Y-connected secondary. transformer.

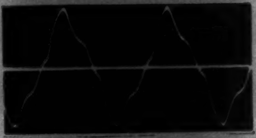
Connected Neutral—Open Delta



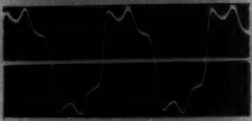
Curve No. 92
Potential, line to line, 745 volts.



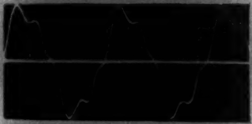
Curve No. 93
Potential across one leg, 430 volts.



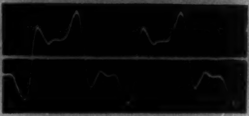
Curve No. 94
Current in line 1, 64.2 amperes.



Curve No. 95
Current in line 2, 57.8 amperes.



Curve No. 96
Current in line 3, 60 amperes.

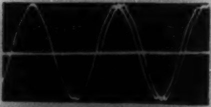


Curve No. 97
Current in connected neutral, 24.9 amperes.

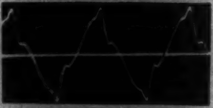
SHEET 17

Oscillograms taken on one three-phase, shell-type, 60-cycle, 430-kw., 13,200-volt delta-connected primary, 430-volt Y-connected secondary transformer.

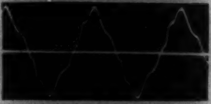
Isolated Neutral—Open Delta



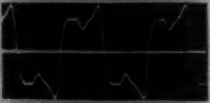
Curve No. 98
Potential, line to line, 745 volts.



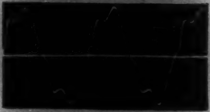
Curve No. 99
Potential across one leg, 460 volts.



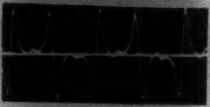
Curve No. 100
Current in line 1, 53.7 amperes.



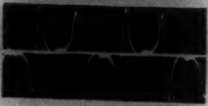
Curve No. 101
Current in line 2, 36.6 amperes.



Curve No. 102
Current in line 3, 53.7 amperes.



Curve No. 103
Potential to isolated neutral, 102.2 volts.

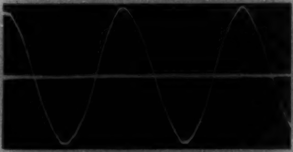


Curve No. 104
Potential across open primary delta, 9580 volts.

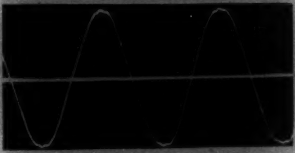
SHEET 18

Oscillograms taken on one three-phase, balanced core-type, 60-cycle, 200-kw., 4600-volt delta-connected primary, 2300-volt Y-connected secondary transformer.

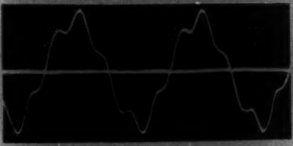
Isolated Neutral—Closed Delta



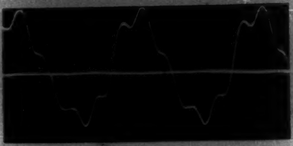
Curve No. 105
Potential, line to line, 3980 volts.



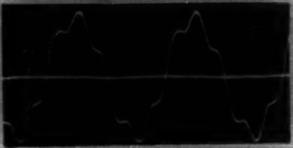
Curve No. 106
Potential across one leg (*i.e.*, line to neutral), 2275 volts



Curve No. 107
Current in line 1, 2.0 amperes.



Curve No. 108
Current in line 2, 1.92 amperes.

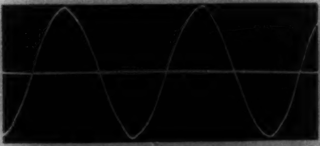


Curve No. 109
Current in line 3, 2.0 amperes.

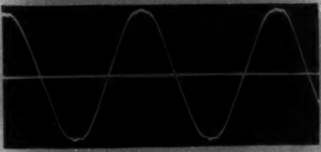
SHEET 19

Oscillograms taken on one three-phase, balanced core-type, 60-cycle, 200-kw., 4600-volt delta-connected primary, 2300-volt Y-connected secondary transformer.

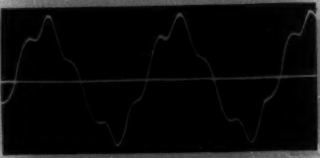
Connected Neutral—Closed Delta



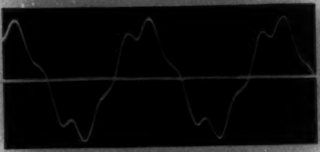
Curve No. 110
Potential, line to line, 3980 volts.



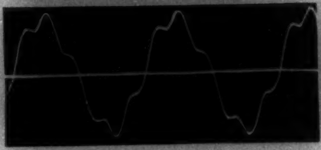
Curve No. 111
Potential across one leg, 2275 volts.



Curve No. 112
Current in line 1, 1.97 amperes.



Curve No. 113
Current in line 2, 1.88 amperes.

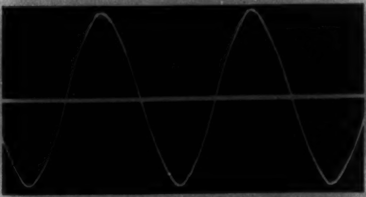


Curve No. 114
Current in line 3, 1.97 amperes.

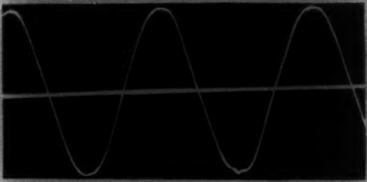
SHEET 20

Oscillograms taken on one three-phase, balanced core-type, 60-cycle, 200-kw., 4600-volt delta-connected primary, 2300-volt Y-connected secondary transformer.

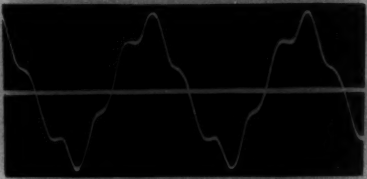
Connected Neutral—Open Delta



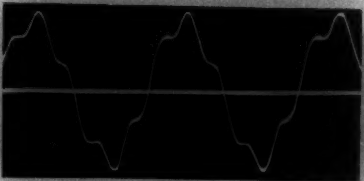
Curve No. 115
Potential, line to line, 3980 volts.



Curve No. 116
Potential across one leg, 2275 volts.



Curve No. 117
Current in line 1, 1.58 amperes.

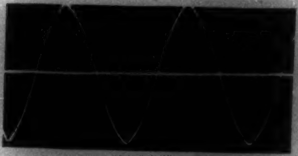


Curve No. 118
Current in line 3, 1.6 amperes.

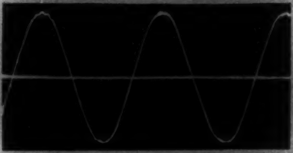
SHEET 21

Oscillograms taken on one three-phase, balanced core-type, 60-cycle, 200-kw., 4600-volt delta-connected primary, 2300-volt Y-connected secondary transformer.

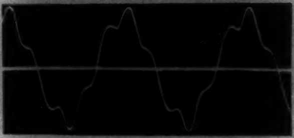
Isolated Neutral—Open Delta



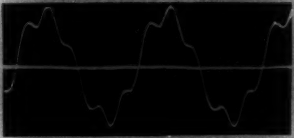
CURVE No. 119
Potential, line to line, 3980 volts.



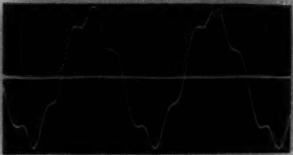
CURVE No. 120
Potential across one leg 2275 volts.



CURVE No. 121
Current in line 1, 1.82 amperes.



CURVE No. 122
Current in line 2, 1.70 amperes.

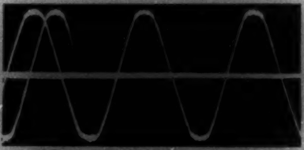


CURVE No. 123
Current in line 3, 1.80 amperes.

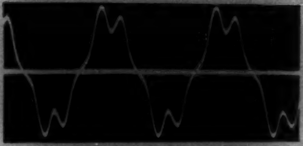
SHEET 22

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt delta-connected secondary.

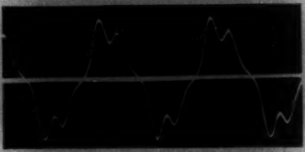
Primary, Closed Delta—Secondary, Closed Delta



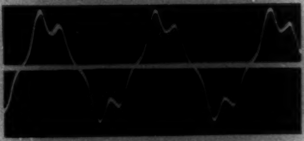
CURVE No. 124
Potential, line to line, 460 volts.



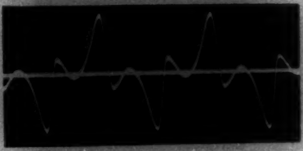
CURVE No. 125
Current in line 1, 11.4 amperes.



CURVE No. 126
Current in line 2, 9.95 amperes.



CURVE No. 127
Current in line 3, 9.7 amperes.

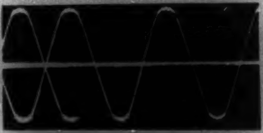


CURVE No. 128
Current in primary delta, 7.1 amperes.

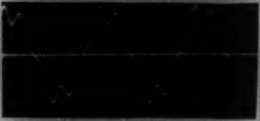
SHEET 23

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt delta-connected secondary.

Primary, Closed Delta—Secondary, Open Delta

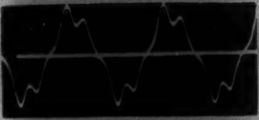


CURVE No. 129
Potential, line to line, 460 volts.

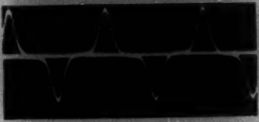


CURVE No. 130
Current in line 1, 11.4 amperes.

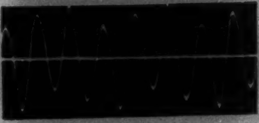
CURVE No. 131
Current in line 2, 9.95 amperes.



CURVE No. 132
Current in line 3, 9.7 amperes.



CURVE No. 133
Current in primary delta, 7.1 amperes.

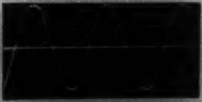


CURVE No. 134
Potential across open secondary delta, 4.7 volts.

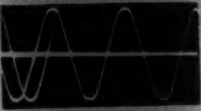
SHEET 24

Oscillograms taken on three single-phase, core-type, 25-cycle, 25-kw., 2300-volt delta-connected primary, 460-volt delta-connected secondary.

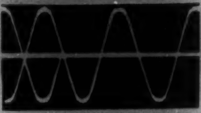
Primary, Open Delta—Secondary, Open Delta



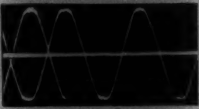
CURVE No. 135
Potential across one leg of primary 2280 volts.



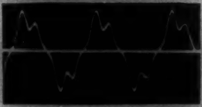
CURVE No. 136
Potential, line 1 to line 3, 460 volts.



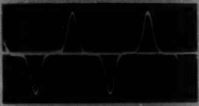
CURVE No. 137
Potential, line 1 to line 2, 460 volts.



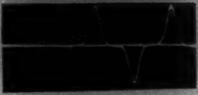
CURVE No. 138
Potential, line 2 to line 3, 460 volts.



CURVE No. 139
Current in line 1, 10.0 amperes.



CURVE No. 140
Current in line 2 7.5 amperes.

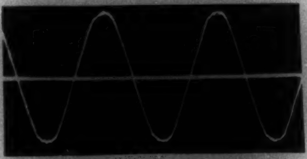


CURVE No. 141
Current in line 3, 5.7 amperes.

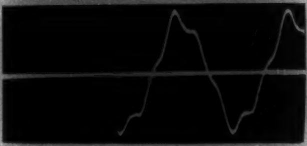
Sheet 25

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt delta-connected primary, 460-volt delta-connected secondary.

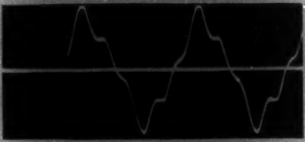
Primary, Closed Delta—Secondary, Closed Delta



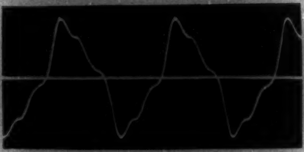
Curve No. 142
Potential, line to line, 430 volts.



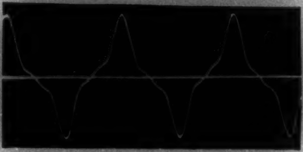
Curve No. 143
Current in line 1, 5.0 amperes.



Curve No. 144
Current in line 2, 4.05 amperes.



Curve No. 145
Current in line 3, 3.6 amperes.

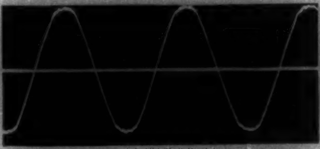


Curve No. 146
Current in primary delta, 2.98 amperes.

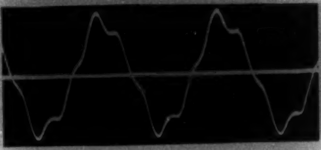
SHEET 26

Oscillograms taken on one three-phase, core-type, 25-cycle, 40-kw., 2300-volt delta-connected primary, 460-volt delta-connected secondary.

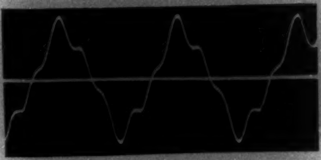
Primary, Closed Delta—Secondary, Open Delta



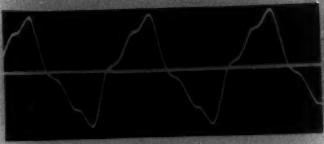
Curve No. 147
Potential, line to line, 430 volts.



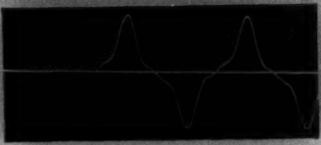
Curve No. 148
Current in line 1, 5.0 amperes.



Curve No. 149
Current in line 2, 3.6 amperes.



Curve No. 150
Current in line 3, 4.05 amperes.

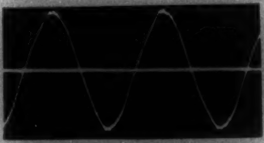


Curve No. 151
Current in primary delta, 2.98 amperes.

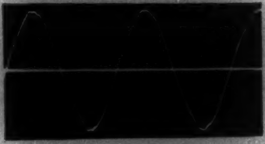
SHEET 27

Oscillograms taken on one single-phase, core-type, 25-cycle, 25-kw 2300-volt primary, 460-volt secondary transformer.

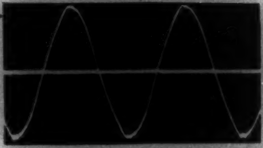
Single Phase



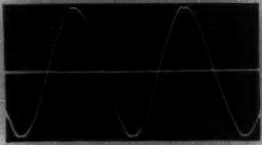
Curve No. 152
Potential at 22.5 kilolines, 115 volts.



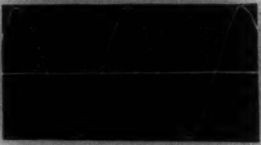
Curve No. 153
Potential at 45.0 kilolines, 230 volts.



Curve No. 154
Potential at 90 kilolines, 460 volts



Curve No. 155
Potential at 112.5 kilolines, 575 volts.

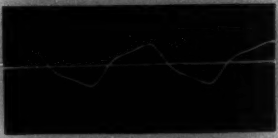


Curve No. 156
Potential at 135 kilolines, 675 volts.

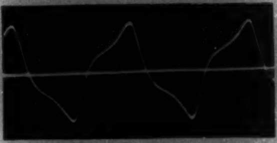
SHEET 27A

Oscillograms taken on one single-phase, core-type, 25-cycle, 25-kw., 2300-volt primary, 460-volt secondary transformer.

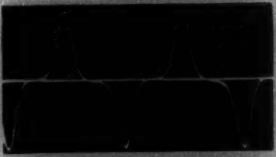
Single Phase



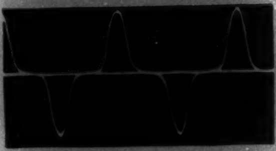
Curve No. 157
Current at 22.5 kilolines, 0.402 amperes.



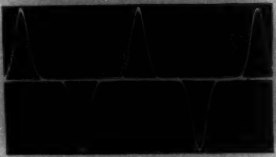
Curve No. 158
Current at 45.0 kilolines, 0.75 amperes.



Curve No. 159
Current at 90 kilolines, 6.05 amperes.



Curve No. 160
Current at 112.5 kilolines, 27.2 amperes.

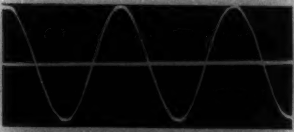


Curve No. 161
Current at 135 kilolines, 113.4 amperes.

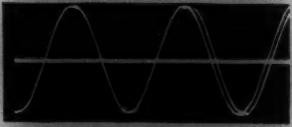
SHEET 28

Oscillograms taken on one alternator at Station No. 3, Rochester Railway and Light Co., Rochester, N. Y. Connected neutral, 24 poles, 2100-kw., 300 rev. per min., 4150 volts.

Load 1500 kw.

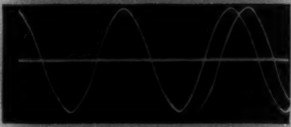


CURVE No. 162
Potential wave, line *A* to line *B*, 4440 volts.

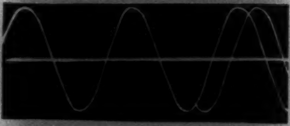


CURVE No. 163
Potential wave, neutral to line *C*, 2560 volts.

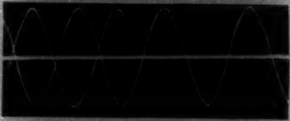
Isolated neutral, 80 poles, 1360 kw., 90 rev. per min., 2500 volts



CURVE No. 164
Potential wave, line *A* to line *B* (no load), 4357 volts.

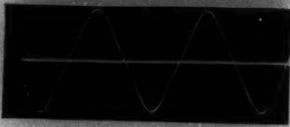


CURVE No. 165
Potential wave, neutral to line *A* (no load), 2455 volts.



CURVE No. 166
Potential wave, neutral to line *C* (no load), 2455 volts.

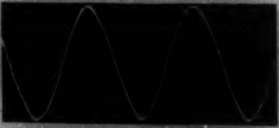
Isolated neutral, 10 poles, 3000 kw., 720 rev. per min., 4150 volts



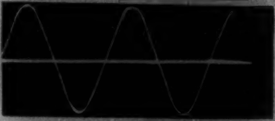
CURVE No. 167
Potential wave, neutral to line *C* (no load), 2487 volts.

SHEET 29

Oscillograms taken on one alternator at Station No. 5, Rochester Railway and Light Co., Rochester, N. Y. Isolated neutral, 22 poles, 1200-kw., 327 rev. per min , 4150 volts.

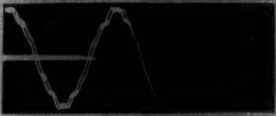


CURVE No. 168
Potential wave, line to line (no load), 4230 volts.

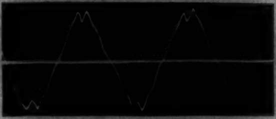


CURVE No. 169
Potential wave, neutral to line (no load), 2718 volts.

Isolated neutral, 16 poles, 350 kw., 450 rev. per min., 2500 volts

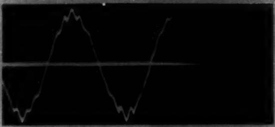


CURVE No. 170
Potential wave, line to line (no load), 4457 volts.

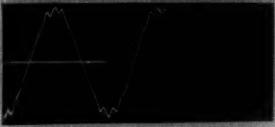


CURVE No. 171
Potential wave, neutral to line (no load), 2540 volts.

Isolated neutral, 24 poles, 530 kw., 300 rev. per min., 4150 volts. Frequency Changer



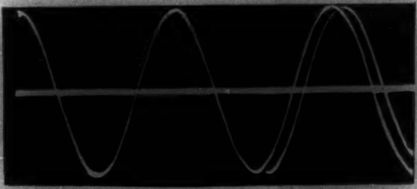
CURVE No. 172
Potential wave, line to line (no load), 4083 volts.



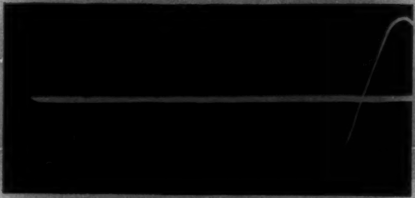
CURVE No. 173
Potential wave, neutral to line (no load), 2277 volts.

SHEET 30

Oscillograms taken on one alternator at Station No. 15, Rochester Railway and Light Co., Rochester, N. Y. Connected neutral, 36 poles, 500 kw., 200 rev. per min., 4150 volts.

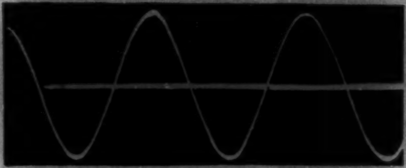


Curve No. 174
Potential wave, line *A* to line *B* (no load), 4,373 volts.

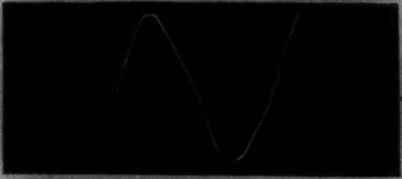


Curve No. 175
Potential wave, neutral to line *C* (no load), 2,400 volts.

Feeders at Station No. 34, Rochester Railway and Light Co., Rochester, N.Y. Transformers disconnected



Curve No. 176
Potential wave, line to line (no load), 4313 volts.



Curve No. 177
Potential wave, ground to line (load, 500 kw.), synchronous motor and 450-kw. transformer, 2473 volts.

in the above tables, as these conclusions were drawn without consideration of any harmonics higher than the third which might be present in the wave shape of the exciting current of the average commercial transformer. A series of tests and investigations with the oscillograph was, therefore, undertaken to check this opinion on the subject and at the same time to make evident, if possible, that the investigation and discussion of current and potential wave shapes has scientific value not only from a theoretical view point, but has great practical value from the operating standpoint as well. It has great bearing on the successful operation of every large alternating current distributing system and must be so considered, as a disregard of the importance or effect of this distortion may lead to dangerous conditions and disastrous results.

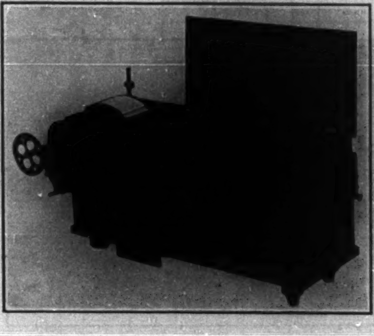


Fig. 2.—Oscillograph showing photographic and tracing attachment

Oscillograms of current and potential wave shapes discussed in the succeeding pages of the paper were taken by an oscillograph similar to that described in the paper by L. T. Robinson, Transactions of the American Institute of Electrical Engineers, Vol. 24, and shown in Figs. 2 and 3.

As the two half cycles of the oscillograph curve are symmetrical, it is necessary for the analysis and subsequent discussion to consider only the first half cycle, which part on an enlarged scale has been transferred by means of a dividing engine to coördinate paper, and resolved into its component curves, of the first, third and fifth, etc., frequencies, by the method described by Professor S. P. Thompson in his book on Dynamo Electric Machinery, Vol. II, and which is given in the appendix to this paper, together with a complete analysis of curve No. 78, Sheet 13, the analysis of which is shown in Fig. 17. The accuracy of the method has been tested by comparing the original complex wave with the complex wave formed by combining the several component curves. In every case, the two complex waves are almost identical.

PLOTTING OF HYSTERESIS LOOP

As a basis for discussion, and as representative of a size and voltage commonly found in practice, a 25-cycle, 185-kw., 33,000-volt primary, 430-volt secondary transformer was selected, on which oscillograms of exciting current were taken with strictly sinusoidal potential applied. Sheet 5 shows the oscillograms corresponding to different densities. The analysis of these curves, given in Figs. 4, 5, 6 and 7, show the characteristic distortion due to the presence of the harmonics. In these figures, the curves marked " complex wave " correspond to the oscillograms on Sheet 5. These complex waves, by the method previously referred to, have been resolved into their component sine waves. The following table gives the values of the maxima of these several curves in terms of the maximum of the complex and also in terms of the maximum of the fundamental wave.

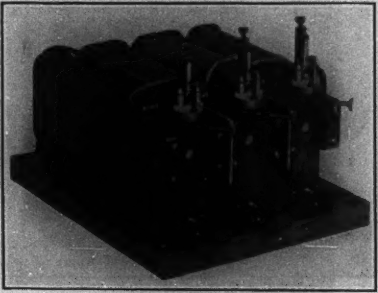
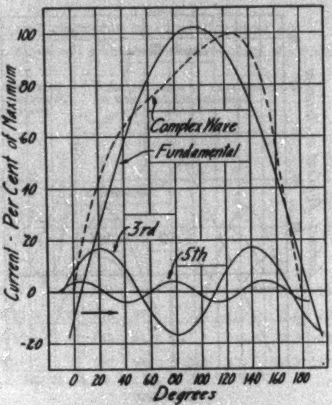


FIG. 3.—Oscillograph galvanometer



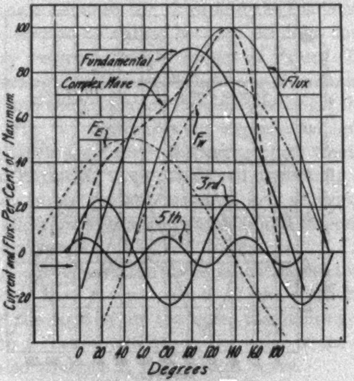
Max. complex wave = 100

$R_1 = 102.6$ $\phi_1 = -6° 16'$

$R_3 = 17.0$ $\phi_3 = 27° 9'$ **25% excitation**

$R_5 = 4.0$ $\phi_5 = 58° 38'$

FIG. 4.—Analysis of oscillogram No. 21 Sheet No. 5



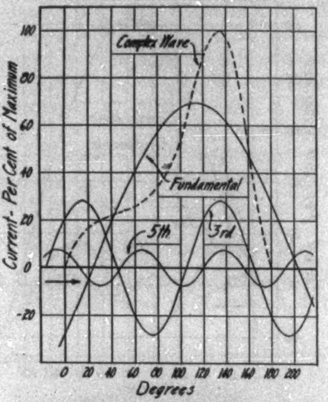
Max. complex wave = 100

$R_1 = 90.7$ $\phi_1 = -11° 52'$

$R_3 = 23.3$ $\phi_3 = 30° 43'$ **50% excitation**

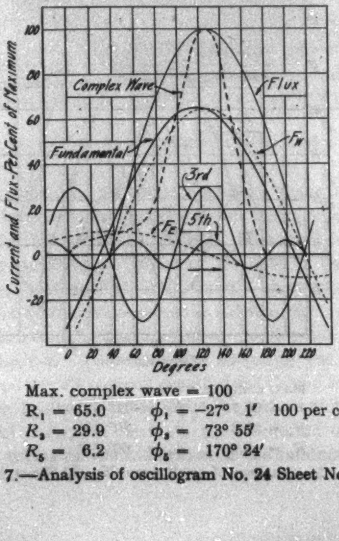
$R_5 = 6.6$ $\phi_5 = 66° 52'$

FIG. 5.—Analysis of oscillogram No. 22 Sheet No. 5



Max. complex wave = 100
$R_1 = 69.4$ $\phi_1 = -23° 50'$ 75 per cent excitation
$R_3 = 28.2$ $\phi_3 = 45° 30'$
$R_5 = 7.7$ $\phi_5 = 120° 0'$

FIG. 6.—Analysis of oscillogram No. 23 Sheet No. 5



Max. complex wave = 100
$R_1 = 65.0$ $\phi_1 = -27° 1'$ 100 per cent excitation
$R_3 = 29.9$ $\phi_3 = 73° 55'$
$R_5 = 6.2$ $\phi_5 = 170° 24'$

FIG. 7.—Analysis of oscillogram No. 24 Sheet No. 5

TABLE I.

DATA RELATIVE TO CURVE IN FIGS. 4–7

25-cycle, 185-kw., 33,000-volt primary, 430-volt secondary, single-phase transformer

	Relative values of maxima in terms of complex wave				Relative value of maxima in terms of fundamental wave							
Density per sq. in. kilolines	Complex wave per cent	Fundamental per cent	Third harmonic per cent	Fifth harmonic per cent	Fundamental per cent	Third harmonic per cent	Fifth harmonic per cent	Complex wave per cent	Amperes effective	Core loss watts	Angle of advance of 3d over fund in terms of fundamentals	Angle of hysteretic advance
22.6	100	102.6	17	4.0	100	16.6	3.9	97.5	3.48	233	15°	31°
45.25	100	90.7	23.3	6.6	100	25.5	7.3	110.0	5.49	730	22°	34°
61.9	100	69.2	28.8	7.7	100	41.6	11.1	144.5	12.5	1488	39°	21°
90.5	100	65.0	29.9	6.2	100	46	9.6	154	35.8	2575	52°	9°

Fig. 8 gives the square root of the mean square value of exciting current and core loss on this transformer at different densities.

It will be seen that these figures do not bear out the conclusion drawn by Dr. Bedell and Mr. Tuttle. It will be noted that ϕ, the angle between the third and the fundamental at the origin, is not limited to values between 30 degs. and 180 degs., but may vary between greater ranges of value. The angle of hysteretic advance, or the angle between the maximum of the fundamental and the maximum flux, may be larger than 30 degs., as shown in Fig. 5. No doubt the explanation for this is due to the fact that in the former discussion, only the fundamental and the third harmonic were considered as forming the complex wave, whereas in the present instance, it is shown that at least the fifth, in addition to the fundamental and the third, is found in the complex waves.

From these curves and the table given above, the conclusion may be drawn that the amplitude of the third harmonic increases with the density in the core, the limiting value being dependent, to a certain extent, on the value of the other higher harmonics also present in the current wave.

In Figs. 5 and 7, curves have been added to represent the flux and, in accordance with conclusion 6, page 667, the maximum of the flux is shown in phase with the maximum of the complex wave. In Fig. 5, the maximum of this flux wave represents a density equal to 45.2 kilolines per square inch, while in Fig. 7, it represents a density of 90.5 kilolines per square inch.

For a further discussion of the curves, the fundamental wave has been resolved into two sinusoidal curves whose maxima are 90 deg. apart; one F_e in phase with the voltage, and one F_w in phase with the flux. The former, in phase with the voltage, represents energy given to the core; that is, hysteretic loss. The latter, 90 deg. out of phase with the voltage and consequently in phase with the flux, represents no power; that is, wattless or that part of the current required merely to magnetize the core. The complex wave, *i.e.*, the oscillogram, has, therefore, been resolved into four component parts; two of fundamental frequency—one, F_w in phase with the flux, the other, F_e in phase with the voltage—and one curve of three times fundamental frequency and one curve of five times fundamental frequency.

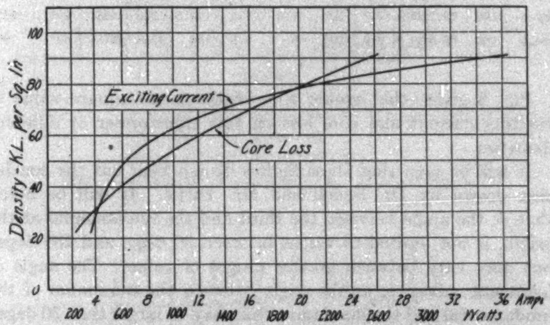


FIG. 8.—Curve of exciting current and losses single-phase core type 25-cycle, 185-kw. 33,000-volt primary, 430-volt secondary transformer.

Using a system of rectangular coördinates, and plotting loops with these various curves in conjunction with the curve of flux, some interesting results follow:

1. Using the complex current and the sinusoidal flux wave, the well-known hysteresis loop may be plotted whose area is equal to, or rather represents, the energy given to the core for any particular induction. In Figs. 9 and 12, the loop marked L_c, is shown corresponding to a density in the core of 45.2 kilolines and 90.5 kilolines per sq. in. respectively.

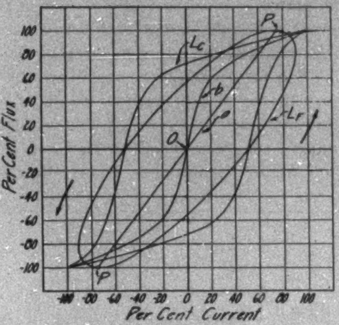


FIG. 9.—Loops plotted from oscillogram No. 21 sheet No. 5 and oscillogram No. 26 Sheet No. 5

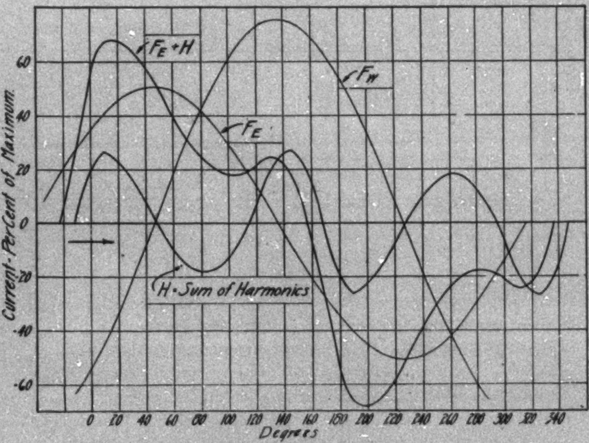


FIG. 10.—Curves obtained from oscillogram No. 22 Sheet No. 5 d oscillogram No. 26 sheet No. 5

2. Using the fundamental component of the current wave instead of the complex wave, *i.e.*, the complex wave minus the higher harmonics, and the sinusoidal flux curve, an elliptical loop, marked L_f, results, of the same area as the distorted loop. This indicates that the same energy is given to the core. The conclusion to be drawn is, that with sinusoidal potential applied, the higher harmonics in the current wave are not produced by, or do not produce, the energy loss in the core.

3. Using the wattless component F_w of the fundamental and

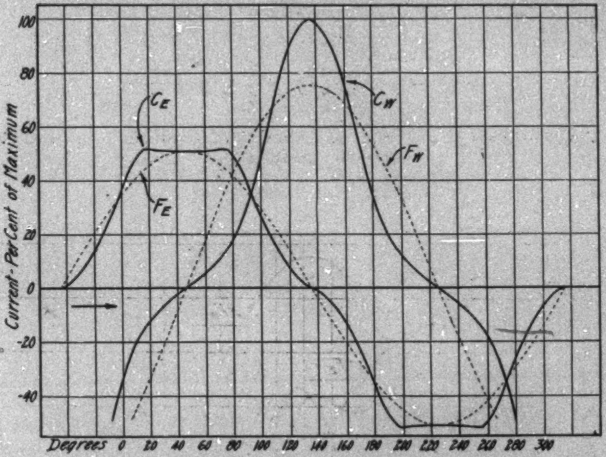


FIG. 11.—Curves obtained from oscillogram No. 22 sheet No. 5 and oscillogram No. 26 sheet No. 5

the sinusoidal flux wave, the straight line curve a, Fig. 9, is obtained, passing through zero and intersecting the ellipse at the point F. Since the wattless component of the current is used in conjunction with the flux curve, the figure should enclose no area, as it represents no loss. It should be noted that the location or relative position of this line a is determined by the magnetizing component of the fundamental of the exciting current. The point P, *i.e.*, the intersection of the straight line a with the ellipse, may be predetermined by using the amplitude of the wattless component of the fundamental as abscissa, plotted against the maximum of the flux as an ordinate. This point P and zero determine the direction of the line. If the magnetizing component of the fundamental were small compared with the energy component, the angle made by this line a with the vertical axis would be small, and were this component large, the angle made by the line a with the vertical would be large. Should it be possible for this component to equal zero, the line a would be vertical and would coincide with the vertical axis of ordinates.

4. Uniting the energy component of the fundamental with the higher harmonics, the curve shown in Figs. 10 and 13, marked F_e+H follows. F_e is the energy component of the fundamental, as shown in Figs. 5 and 7, and curve H is the sum of the harmonics; *i.e.*, the complex wave minus the fundamental. Using ordinates of this curve F_e+H as abscissa, and line a as an axis, the original hysteresis loop L_c, Fig. 9 will result. The ordinates of this curve F_e+H, Fig. 10, above the zero line are plotted to the right of line a, Fig. 9, and the ordinates of F_e+H, Fig. 10, below the zero line are plotted to the left of line a, Fig. 9. Since the sinusoidal flux wave has again been combined with the energy, wattless, and harmonic components of the current, the resultant figure should be the hysteresis loop originally plotted.

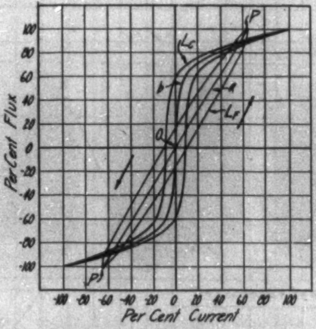


FIG. 12.—Curves plotted from oscillogram No. 24 sheet No. 5 and oscillogram No 26 sheet No. 5

5. Using the energy component F_e of the fundamental, and

the sinusoidal flux wave, an ellipse or circle will result, not shown, but vertical with respect to the axis of coördinates.

6. Using the wattless component of the fundamental F_w, Fig. 10, and all the harmonics in phase with the flux, curve H, Fig. 10, and plotting a curve with the flux, the line b, Figs. 9 and 12 results. This line should enclose no area since only wattless components of the current wave are used. It is analogous to line a, but is bent or distorted, due to the presence of harmonics. It represents also the average current required for rising and falling magnetization.

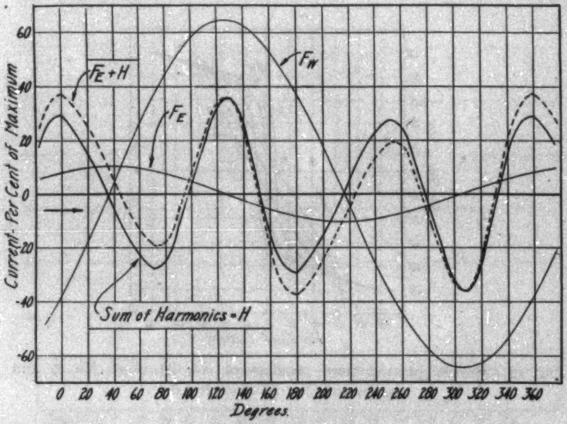


FIG. 13.—Curves plotted from oscillogram No. 24 sheet No. 5 and oscillogram No. 26 sheet No. 5

7. Considering Figs. 5 and 7, attention is called to the fact that the maximum of the third and of the fifth harmonic are not in phase with the maximum of the flux or of the complex wave. If these harmonics are resolved into component parts in phase with the flux and in phase with the voltage, and these components added to similar ones of the fundamental, curves C_w and C_e will result. These curves may also be obtained from curves given in Figs. 5 and 9, as follows:

C_e may be obtained by using as ordinates the abscissa between line b and the hysteresis loop; curve C_w by using as ordinates the abscissa between the vertical axis and the line b.

It is interesting to note that the area enclosed between the curve F_e, Fig. 11, and the horizontal axis, is equal to the area enclosed between the horizontal axis and the curve C_e, Fig. 11. Since this area, in a certain sense, represents the energy supplied the core, we can again conclude that the harmonics do not affect the loss in the core.

The general conclusion to be drawn from these tests and the interpretation of the various curves plotted is that in transformers the distortion of the current wave shape is neither a cause nor an effect of the energy loss in the core, but results only from the varying permeability of the steel. The amount of the distortion varies with the density, since the greater the density the more prominent are the higher harmonics, such as the third, fifth, seventh, ninth, etc.

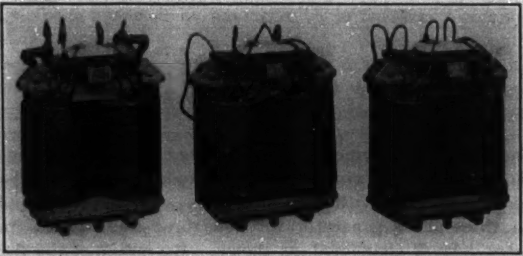


Fig. 14.—Three, single-phase, core-type, 25-cycle, 25-kw. 2300-volt primary, 460 volt secondary transformers used in observing third harmonics

INVESTIGATION OF INTERCONNECTED TRANSFORMERS

As an extension to the investigation of a single-phase transformer, observations of harmonics in current and potential wave shapes of interconnected transformers were made. With three transformers, the Y-connection is the most common, and without doubt, the most important connection. For these observations, three single-phase, core-type, 25-cycle, 25-kw., 2300-volt primary, 460-volt secondary transformers were selected, and oscillograms taken of current and potential at different densities in the core. The small capacity was selected so that the potential wave shape of the relatively small generator available would not be distorted by the current required for the test; the low voltage to avoid the use of both current and potential transformers in measuring current, voltage, and watts.

As preliminary and for further reference, oscillograms of potential and current at different densities were taken single-phase and are shown on Sheets 27 and 27 A. The only special reference to be made to these current curves is the pronounced flattening at the zero point for the higher densities. Root-mean-square values are give in Table 2.

TABLE 2

25-cycle, 25-kw., 2300-volt primary, 46-volt secondary transformers, connected single-phase

B-Kilolines	Volts	Amperes	Watts
45.0	230	0.75	70
90.0	460	6.05	280
112.5	575	27.2	540

The three transformers were connected as shown in Fig. 15 with the 460-volt winding Y-connected, and the 2,300-volt winding connected with the delta open. Current was supplied by a three-phase generator through three single-phase transformers delta-Y connected, as shown. By means of the switch at $E F$, the neutrals between the step-down transformers and the transformers under test could be connected; with the switch at $B C$, the delta connection of the transformer under test could be closed.

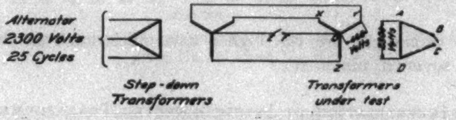


FIG. 15

With the switches at $B C$ and $E F$ open, root-mean-square values of current in the line and voltage across the Y, *i.e.*, across $X Z$, $X Y$ and $Y Z$; across the leg, *i.e.*, $O X$, $O Y$ and $O Z$; and across the open delta, and across the open neutral are given in Table 3.

TABLE 3

Three 25-cycle, 25-kw., 2,300-volt primary, 460-volt secondary transformers, connected open delta—isolated neutral

Density in core kilolines per sq. in.	Voltage across				Current in line			Watts
	Lines	Leg	Open delta	Isolated neutral	1	2	3	
22.5	397.5	244.6	1,180	100	0.53	0.54	0.54	167.5
90.0	795	525	3,780	257	3.42	3.27	3.42	675
112.5	995	675	5,040	330.5	15.5	14.3	15.7	1,650

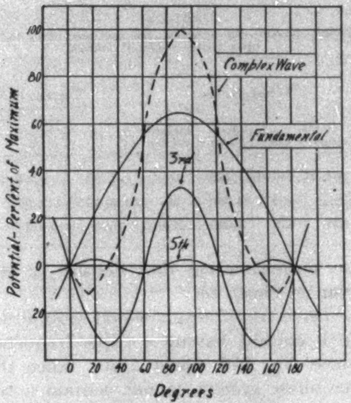
Oscillograms corresponding to a density of 90 kilolines per sq. in. are given in Sheet 13.

Each of the three transformers would require normally for its magnetization a current having a triple frequency component similar to curve No. 159, Sheet 27A. Since the current in a balanced three-phase system cannot contain a triple harmonic (otherwise the sum of the instantaneous values would not equal zero), the current wave shape in Y-connected transformers cannot contain a triple harmonic. Necessarily, the induction in the core must be distorted from the sine shape by an amount corresponding to the value of the triple harmonic component in the current. The resulting induction in the core of each transformer is, therefore, represented by the potential curve No. 77, Sheet 13, and the current flowing in the winding, by curve No. 78, Sheet 13. The analyses of these curves are given in Figs. 16 and 17.

In Fig. 16, attention is called to the relative values of the maximum induction at fundamental, triple, and quintuple frequencies, equal to 64.5 per cent, 33.3 per cent and 2.2 per cent respectively, of the maximum of the complex wave.

In Fig. 17, attention is called to the absence of the triple frequency component of the current and to the pronounced quintuple component. It will be noted also that the sum of the induction at triple and quintuple frequency is equal to 55 per cent of the maximum induction at the fundamental frequency.

Fig. 18 shows the instantaneous values of potential across each of the delta-connected windings of the transformers in their proper phase relation to each other. The triple frequency components in the legs are in phase with each other while the fundamental components are 120 deg. apart and their sum equals zero. The voltage in the delta is, therefore, represented by the curve *C B*, Fig. 18, and measured by curve No. 80, Sheet 13. Both curves show a triple frequency potential equal in ampli-



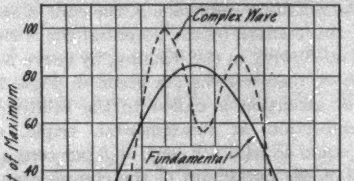
Max. complex wave = 100

$R_1 = 64.5$ $\phi_1 = -0°\ 32'$

$R_3 = 33.3$ $\phi_2 = 177°\ 56'$

$R_5 = 2.2$ $\phi_3 = -15°\ 58'$

FIG. 16.—Analysis of oscillogram No. 77 sheet No. 13



Max. complex wave = 100

$R_1 = 84.2$ $\phi_1 = 14°\ 2'$

$R_5 = 21.9$ $\phi_5 = 77°\ 21'$

$R_7 = 3.2$ $\phi_7 = 214°\ 43'$

FIG. 17.—Analysis of oscillogram No. 78 sheet No. 13

tude to three times that of the triple frequency found in each leg. The root-mean-square voltage read across the open delta is given in Table 3 and confirms the conclusion drawn from the discussion of the curves.

While the sum of the instantaneous current values is equal to zero, the resultant distortion of the potential produces an unbalance in the voltage of the system; *i.e.*, the sum of the instantaneous potential values does not equal zero as is evidenced by the voltage across the open delta and the open neutral.

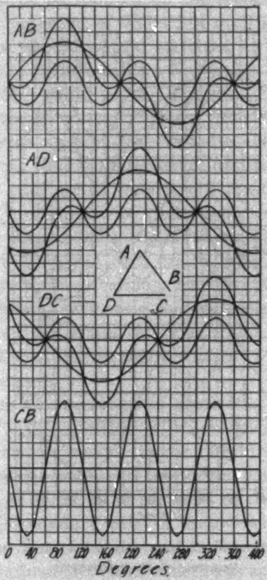


FIG. 18.—Phase relation of voltage across legs and across open delta of delta-connected transformers

In Fig. 19 is shown the instantaneous values of potential across the transformer, *O* X and *O Y*, and across the lines, X *Y* in their proper phase relation. It will be noted that the sum of the instantaneous values of *O* X and *O Y* equals the instantaneous values of X *Y*. The triple frequency components of voltage being 60 degs. fundamental frequency, or 180 degs. triple frequency apart, neutralize each other, and the resultant potential across the Y is a sine shape.

The potential across X Y, X Z, and Y Z is a sine curve, as shown by curve No. 76, Sheet 13, and by Fig. 19. By the connections shown in Fig. 15, a sine potential is insured across each leg of the delta-Y step-down transformers. It has just been noted that the potential across each leg, O X, O Y, and O Z is not a sine potential (see Sheet 15), so that the system is unbalanced with respect to the potential across the neutral $E F$ by an amount equal to the triple frequency distortion found in each leg. Curve No. 79, Sheet 13, gives the observed shape.

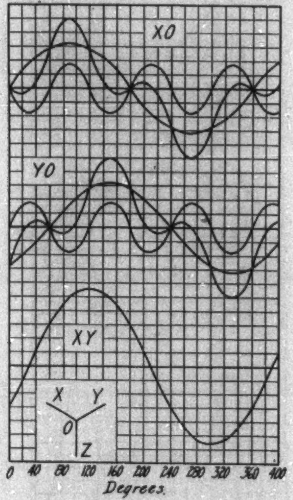


FIG. 19.—Phase relation of voltage across line and across legs of Y-connected transformers

Root-mean-square values given in Table 3 confirm the above conclusions. With 795 volts applied across the Y, (*i.e.*, X Y) the voltage across each leg is not $\frac{795}{\sqrt{3}}$, (*i.e.*, 460 volts) but 525 volts. Since effective voltages of different frequencies are added in quadrature, the value of the higher harmonic component is $\sqrt{525^2 - 460^2} = 253$ volts, which agrees quite closely with 257 volts actually read across the open neutral. It should be noted also that 253 volts is 55 per cent of 460, agreeing perfectly with the observation in the discussion of Fig. 16.

Since the distortion applied to the primary winding of the transformer must be reproduced on the secondary winding, the triple frequency potential of 253 volts multiplied by the ratio of transformation should appear on each leg of the delta-connected side of the transformers. The ratio of transformation being 5:1, $5 \times 253 = 1265$ volts. This multiplied by 3—since the triple frequency voltage in the three legs is in phase—gives 3795 volts as against 3780 volts actually observed.

It may be noted that with 795 volts applied across the lines, 2620 volts were read across each leg of the delta, indicating a change or error in the ratio of transformation. This fictitious ratio will not be observed if voltages are read across the primary and secondary windings of each transformer. With 525 volts applied to the low tension winding, 2,620 volts is observed on the high tension winding, indicating the correct ratio. As the discrepancy between the actual ratio and this apparent ratio is due entirely to the triple frequency voltage it disappears as soon as the delta is closed.

The discussion of transformers connected as above applies equally well to any connection in which neither winding of the transformer forms a closed delta, or in which the neutrals are isolated. In several instances, the writer has observed a triple frequency voltage equal to 50 per cent of the fundamental appearing on the secondary side of step-down transformers for synchronous converters, so that when the converters were disconnected, the ratio of the transformers was apparently decreased 20 per cent. This decrease in ratio, of course, immediately disappeared as soon as the synchronous converters were put into operation.

The important detail to be noted in the observations made of this Y-delta connection is the increase in the potential strains distributed throughout the winding of the transformer resulting from the distorted potential wave shape. Excepting in small lighting transformers, where the insulation factor of safety is 5 or 10, this increase in the potential strains greatly reduces the reliability of operation of a transformer. In such transformers in which the normal fundamental voltage is 70,000 or 80,000 volts and which have an insulation factor of safety of about two, as indicated by the test voltage of 140,000 to 160,000 volts applied, the application of a triple frequency voltage of 40 per cent or 50 per cent of the fundamental may reduce the insulation factor of safety to 1.3 or 1.4—certainly not large enough to insure reliable operation. It should be noted also, from Table 3 and Fig. 16, that while the root-mean-square value of the potential is increased about 25 per cent, the maximum value of the complex wave is very much more increased and since the maximum is the puncturing voltage, the actual increase in the voltage strain is not truly indicated by the root-mean-square values as given in Table 3.

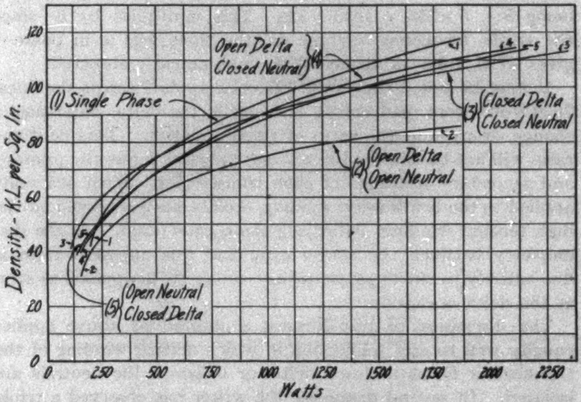


FIG. 20.—Curve of core losses: three single-phase, 25-cycle 25-kw. 2300-volt primary, 460-volt secondary transformers

The distinction between these strains and those resulting from high frequency surges should be clearly noted. The strains resulting from this potential distortion are equally distributed over all parts of the winding, while those resulting from line surges, short circuits or switching may affect only a small portion of the winding. Attention is also called to the difference in the losses in transformers. Referring to Table 1, we note that, under single-phase excitation, the core loss in each transformer at a density of 90 kilolines is 280 watts, or 840 for the three transformers, while with the same effective voltage on the transformers connected three-phase, the total core loss is but 675 watts. This difference or reduction in loss is explained by the difference in the maxima of the density in the core under the different connections. Fig. 20 brings out more clearly this difference in core loss under the different connections.

The next step in the discussion is to observe the results obtained from the elimination of the potential distortion cited above by closing the delta. Oscillograms of current and potential are given on Sheet 10. The root-mean-square values are given in Table 4.

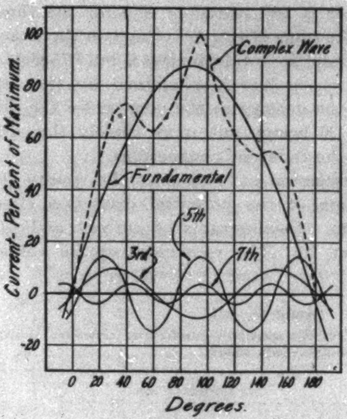
TABLE 4

25-cycle, 25-kw., 2300-volt primary, 460-volt secondary transformers, connected neutral isolated—delta closed.

B-Kilolines	Voltage across			Current in line				Watts
	Lines	Leg	Isolated neutral	1	2	3	Closed delta	
22.5	397.5	234.6	0	0.59	0.58	0.60	0	188
90.0	795	462.5	0	6.30	5.4	5.73	0.63	1,030
112.5	995	575	0	27.7	24.0	27.0	3.2	2,060

It will be noted that the potential wave across the transformers, as well as across the lines X Y, has a sine shape and that the voltage across the open neutral has dropped to zero. This is to be expected from our previous discussion, as the triple frequency harmonic of the current has now been supplied. The value of this current necessary to demagnetize the core is indicated by the 0.63 ampere read in the closed delta. Analysis of oscillogram 65, Sheet 10, is given in Fig. 21, and of oscillogram 66, Sheet 10, is given in Fig. 22. It will be noted that upon closing the switch at C D with 3780 volts observed across the open delta, only a very small current flows. This is consistent as the current is in no sense a load current, but merely the triple frequency exciting current component necessary to demagnetize the core to eliminate the potential distortion.

If, instead of supplying the triple frequency current component by closing the delta, it is supplied by connecting the neutrals at E F, the same general results follow, as is shown by the oscillograms on Sheet 12. It will be noted that practically



Max. complex wave = 100

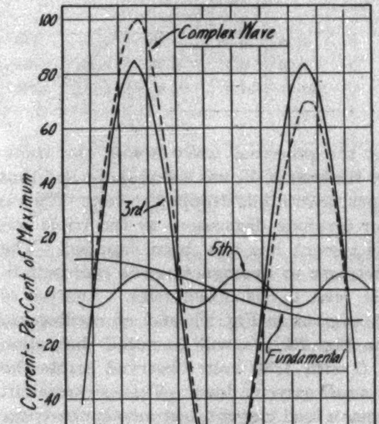
$R_1 = 88.1$ $\phi_1 = 2° 13'$

$R_3 = 9.4$ $\phi_3 = -3° 32'$

$R_5 = 14.4$ $\phi_5 = -24° 13'$

$R_7 = 3.8$ $\phi_7 = 148° 12'$

FIG. 21.—Analysis of oscillogram No. 65 sheet No. 10



Max. complex wave = 100

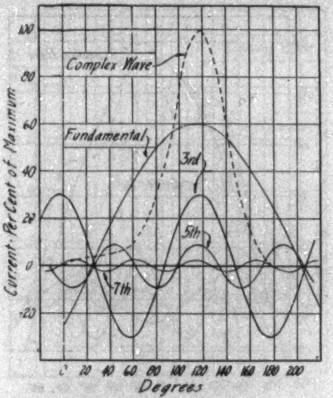
$R_1 = 11.2$ $\phi_1 = 88° 28'$

$R_3 = 83.8$ $\phi_3 = -3° 24'$

$R_5 = 6.0$ $\phi_5 = -87° 9'$

FIG. 22.—Analysis of oscillogram No. 66 sheet No. 10

sine potential is applied to each of the transformers, as shown by oscillogram 72, and that the current wave in the transformers has been restored to practically the identical shape required when excited single-phase. A comparison of curve No. 73, sheet 12, and its analysis given in Fig. 23, should be made with curve No. 159, Sheet 27. It will be noted also that the ratio of triple frequency current in the closed neutral to the triple frequency in the closed delta checks with the ratio of triple frequency voltage across the open neutral to the voltage across the open delta. Root-mean-square values are given in Table 5.



Max. complex wave = 100

$R_1 = 60.0 \qquad \phi_1 = -23° \ 39'$

$R_3 = 30.2 \qquad \phi_3 = 98° \ 15'$

$R_5 = 9.0 \qquad \phi_5 = 228° \ 4'$

$R_7 = 2.5 \qquad \phi_7 = 20° \ 43'$

FIG. 23.—Analysis of oscillogram No. 73 sheet No. 12

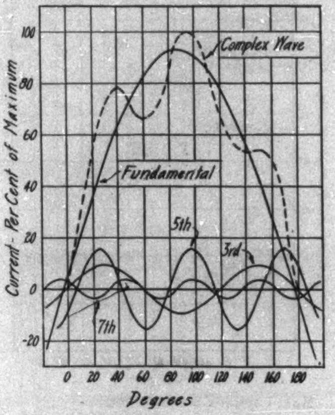
TABLE 5

Three single-phase, core type, 25-cycle, 25-kw., 2300-volt primary, 460-volt secondary transformers, connected delta open—neutral connected

B-Kilolines	Voltage across			Current in line				Watts
	Lines	Leg	Open delta	1	2	3	Connected neutral	
22.5	397.5	232.9	0	0.60	0.64	0.59	0.455	185
90.0	795	462.5	24.5	6.51	4.83	6.48	9.45	970
112.5	995	575	135	33	26	31.7	46.5	1,975

The final investigation is to note the condition existing with both the neutral and the delta closed. Oscillograms are given on Sheet 11; analyses of curves No. 69 and No. 70 are given in Figs. 24 and 25. Root-mean-square values are given in Table 6.

In order to bring out more clearly the difference in core loss in the transformers under different excitations and different connections, the observations have been plotted in curves shown in Fig. 20.



Max. complex wave = 100

$R_1 = 93.2 \qquad \phi_1 = 2° 50'$

$R_3 = 9.4 \qquad \phi_3 = 1° 49'$

$R_5 = 14.9 \qquad \phi_5 = -33° 9'$

$R_7 = 3.8 \qquad \phi_7 = 130° 17'$

FIG. 24.—Analysis of oscillogram No. 69 sheet No. 11

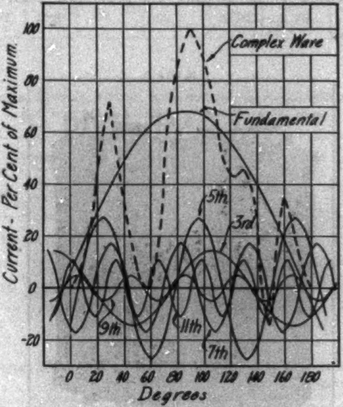
TABLE 6

Three single-phase, core type, 25-cycle, 25-kw., 2300-volt primary, 460-volt secondary, transformers connected delta closed—neutral connected

B-Kilolines	Voltage across		Current in line					Watts
	Lines	Leg	1	2	3	Closed delta	Connected neutral	
22.5	397.5	234.2	0.3	0.28	0.3	0	0	127.5
90.0	795	462.5	4.08	3.45	4.11	0.62	0.76	975
112.5	995	575	27	24.5	27.5	3.2	1.13	2,290

OBSERVATIONS ON A THREE-PHASE CORE TYPE TRANSFORMER

The next step in the investigation was to observe the wave shapes of current and potential on a three-phase core type transformer and to note the influence of the difference in the magnetic circuit of such a transformer as compared with the magnetic circuit of three single-phase transformers. Fig. 26 shows the three-phase core type transformer used in this investigation. As before, a transformer of low voltage and small capacity was selected so that the potential wave shapes applied by the generator would not be distorted by the current required for the test. It should be noted that the magnetization of each of the three legs of the three-phase core is not the result of the current flowing in the coil surrounding it, but is imposed by the resultant effect of the currents around all the legs. The lack of symmetry



Max. complex wave = 100

$R_1 = 68.1$ $\phi_1 = 4° 55'$

$R_3 = 14.2$ $\phi_3 = 132° 32'$

$R_5 = 27.3$ $\phi_5 = -30° 48'$

$R_7 = 17.1$ $\phi_7 = 246° 35'$

$R_9 = 4.9$ $\phi_9 = 46° 25'$

$R_{11} = 10.9$ $\phi_{11} = 70° 44'$

FIG. 25.—Analysis of oscillogram No. 70 sheet No. 11

between the magnetic circuit of the middle leg and either outside leg also affects the results. The reluctance of the air circuit for each leg being many times the reluctance of the iron circuits, considerably more triple frequency current is required to eliminate the potential distortion, so that the marked distortion of current and potential noted in the single-phase transformers under similar connections is, therefore, absent.

Sheets 6, 7, 8 and 9 give oscillograms of current and potential as before. Tables 7, 8, 9 and 10 give the root-mean-square values.

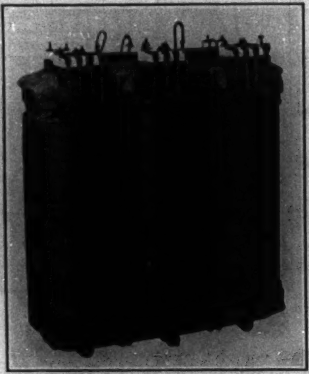


FIG. 26.—Three-phase, core-type, 25-cycle, 40-kw., 2300-volt primary, 460-volt secondary transformer used to investigate third harmonics

TABLE 7

Three-phase, core type, 25-cycle, 40-kw., 2300-volt primary, 460-volt secondary transformers, connected neutral isolated—delta open

B-Kilolines	Voltage across				Current in line			Watts
	Lines	Leg	Open delta	Isolated neutral	1	2	3	
42.6	1150	662	2.5	2.3	0.252	0.234	0.186	210
85.2	2300	1324	50	45	1.34	1.22	1.92	860
106.4	2875	1650	150	135	3.32	2.94	2.64	1960

TABLE 8

Three-phase, core type, 25-cycle, 40-kw., 2300-volt primary, 460-volt secondary transformers, connected isolated neutral—closed delta

B-Kilolines	Voltage across			Current in line				Watts
	Lines	Leg	Isolated neutral	1	2	3	Closed delta	
42.6	1150	662	0	0.234	0.252	0.210	0.076	211.5
85.2	2300	1324	0	1.17	1.32	0.92	0.84	880
106.4	2875	1650	0	3	3.36	2.76	2.93	2040

TABLE 9

Three-phase core type, 25-cycle, 40-kw., 2300-volt primary, 460-volt secondary transformers, connected neutral connected—delta open

B-Kilolines	Voltage across			Current in line				Watts
	Lines	Leg	Open delta	1	2	3	Connected neutral	
42.6	1150	659	0	0.204	0.195	0.171	0.137	213
85.2	2300	1324	0	1.42	1.22	0.92	0.86	880
106.4	2875	1652.5	4	3.16	2.96	2.76	3.25	2040

TABLE 10

Three-phase, core type, 25-cycle, 40-kw., 2300-volt primary, 460-volt secondary transformers, connected delta closed—neutral connected

B-Kilolines	Voltage across		Current in line					Watts
	Lines	Leg	1	2	3	Closed delta	Connected neutral	
42.6	1150	662	1.08	0.096	0.09	0.225	0.223	216
85.2	2300	1324	1.32	1.27	0.82	0.82	0.404	960
106.4	2875	1652.5	3.16	3.26	2.56	3.0	0.7	2120

It should be noted that the potential wave shape across the different legs is not identical, and that the current wave shape in the three legs is also not identical. These differences are explained by the lack of symmetry of the magnetic structure of the different legs and also by the slight difference in the windings of the legs. It will be noted that the same general results follow on the three-phase transformer as were observed in the discussion of the three single-phase transformers.

In Fig. 27, the observed core losses under the different connections are plotted.

The next step in the investigation was the consideration of a three-phase core type transformer with legs symmetrically arranged, as shown in Fig. 28. Oscillograms are given on Sheets 18, 19, 20 and 21, and root-mean-square values at density of 66 kilolines in the core are given in Table 11.

Attention is called to the almost equal values of exciting current for the different windings which was not observed in the unsymmetrical three-phase core type. It will be noted also that as the results of the symmetrical magnetic structure and the inter-relation of the magnetizing effects, the potential wave shape across the different legs under all connections is practically the same. No doubt, at higher densities, some unbalanced effect would be noted, but at the densities at which tests were taken, none were observed.

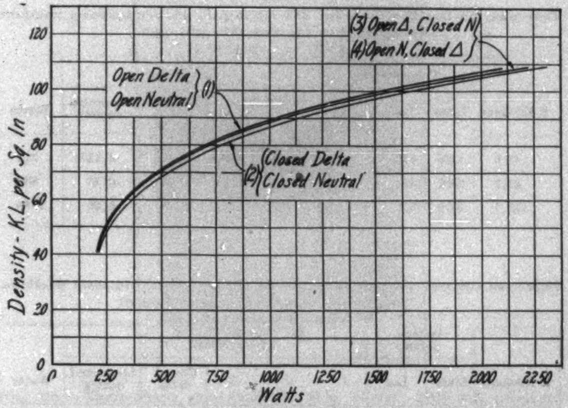


FIG. 27.—Curve of core loss of three-phase, 25-cycle, 40-kw. 2300-volt Y-primary, 460 volt delta secondary

For a final series of observations, a three-phase shell type, 60-cycle, 330-kw., 13,200-volt primary, 430-volt secondary transformer was selected, and oscillograms of current and potential observed as given in Sheets 14, 15, 16 and 17. Root-mean-square values at 43 kilolines and 86 kilolines are given in Tables 12 and 13.

TABLE 11

Three-phase, core type, 60-cycle, 200-kw., 4600-volt primary, 2300-volt secondary transformers.

		Voltage across				Current in line			
	B-Kilolines	Lines	Leg	Neutral	Delta	1	2	3	Watts
(1)	66	3980	2275	0	0	1.82	1.70	1.90	3420
(2)	66	3980	2275	0	0	1.97	1.88	1.97	3820
(3)	66	3980	2275	0	0	1.58	1.42	1.6	3610
(4)	66	3980	2275	0	0	2.0	1.92	2.0	3850

(1) Delta closed—neutral connected.
(2) Delta open—neutral isolated.
(3) Delta closed—neutral isolated.
(4) Delta open—neutral connected.

TABLE 12

Three-phase, shell type, 60-cycle, 330-kw., 13,200-volt primary, 430-volt secondary

		Voltage across				Current in line				
	B-Kilolines	Lines	Leg	Delta	Neutral	1	2	3	Neutral	Watts
(1)	43	372.5	215	4500	50.1	6.0	6.2	4.76	—	2225
(2)	43	372.5	215	—	—	5.88	6.00	4.86	0	2250
(3)	43	372.5	215	5	—	5.88	6.31	5.37	2.33	2275
(4)	43	372.5	215	—	0	6.0	6.2	4.76	—	2225

(1) Delta closed—neutral connected.
(2) Delta open—neutral isolated.
(3) Delta closed—neutral isolated.
(4) Delta open—neutral connected.

TABLE 13

Three-phase, shell type, 60-cycle, 330-kw., 13,200-volt primary, 430-volt secondary

		Voltage across				Current in line				
	B-Kilolines	Lines	Leg	Delta	Neutral	1	2	3	Neutral	Watts
(1)	86	745	460	9580	102.2	53.7	53.7	36.6	—	9,000
(2)	86	745	430	—	—	60	57.8	45.6	3.5	10,500
(3)	86	745	430	301.5	—	64.2	57.8	60.0	24.9	10,200
(4)	86	745	430	—	0	58.8	57.8	44.6	—	10,000

(1) Delta closed—neutral connected.
(2) Delta open—neutral isolated.
(3) Delta closed—neutral isolated.
(4) Delta open—neutral connected

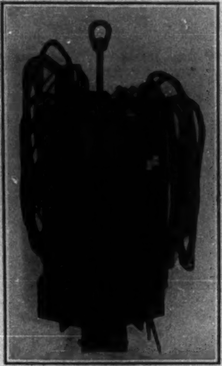


Fig. 28.—Three-phase, core-type, 25-cycle, 500-kw., 2300-volt primary 2300-volt secondary transformer used in the investigation of third harmonics

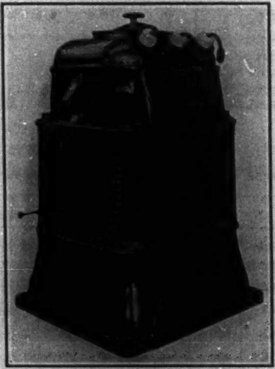


Fig. 29.—Three-phase, shell-type, 60-cycle, 330-kw., 13,200-volt primary, 430-volt secondary transformer used to investigate third harmonics

The general construction of the transformer and diagram of the core structure is shown in Figs. 29 and 30. The unsymmetrical current and potential waves are no doubt explained entirely by the unsymmetrical core structure.

Attention is called to the potential wave shape across the open neutral and open delta, analysis of which is given in Fig. 31. The presence of a fundamental of considerable magnitude is, no doubt, explained by the presence of unbalanced fundamental voltage due to lack of absolute duplication of the windings.

DELTA-CONNECTED TRANSFORMERS

The remaining important connection of interconnected transformers is the delta connection, using either two or three transformers. For this investigation three 25-cycle, 25-kw., 2300-volt primary, 460-volt secondary transformers were selected and connected as shown in Fig. 32. Sheet 22 gives the oscillograms of current and potential, using the three transformers with delta primary and delta secondary. It will be noted that the currents in the line are almost identical in shape. Reference is made to curve No. 78, Sheet 13, and its analysis given in Fig. 17, which shows no third harmonic, but a decided fifth and seventh.

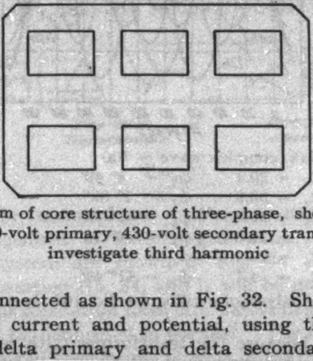
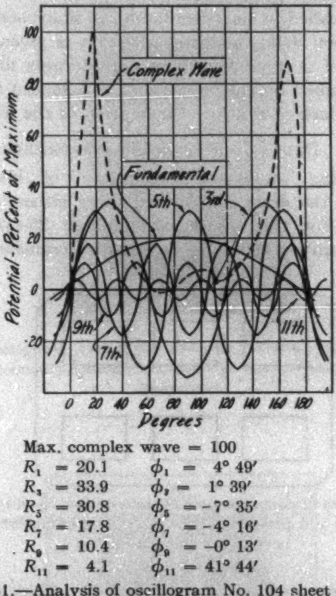


FIG. 30.—Diagram of core structure of three-phase, shell-type, 60-cycle, 330-kw., 13,200-volt primary, 430-volt secondary transformer used to investigate third harmonic

Sheet 23 gives the oscillograms of current and potential with three transformers delta connected on the primary and two transformers on the secondary, a condition which may arise when one of three delta connected transformers becomes open. It will be noted that there is no appreciable change in the current wave shape. The potential across the open delta shows the usual characteristic of triple frequency voltage and a slight fundamental. The current in the primary delta has the characteristic curve of the current in a transformer connected single-phase *i.e.*, has a fundamental and a decided third harmonic. This



Max. complex wave = 100
$R_1 = 20.1$ $\phi_1 = 4° 49'$
$R_3 = 33.9$ $\phi_3 = 1° 39'$
$R_5 = 30.8$ $\phi_5 = -7° 35'$
$R_7 = 17.8$ $\phi_7 = -4° 16'$
$R_9 = 10.4$ $\phi_9 = -0° 13'$
$R_{11} = 4.1$ $\phi_{11} = 41° 44'$

Fig. 31.—Analysis of oscillogram No. 104 sheet No. 17

naturally follows because the transformer with secondary open is excited by the delta connected primary and calls for a current characteristic corresponding to the sine potential applied.

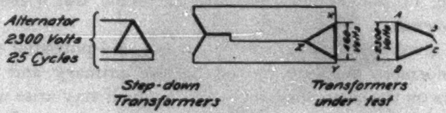

Alternator
2300 Volts
25 Cycles
X
Y
Z
160 Volts
2300 Volts
A
B
C
Step-down
Transformers
Transformers
under test

Fig. 32

The next step in the investigation was to open the primary delta as shown in Fig. 33. Sheet 24 gives the oscillograms. It will be noted that the wave shapes across the lines and across each transformer are identical. The current in the two outside legs shows the usual characteristic of the fundamental and a marked third harmonic. The current in the middle leg, however, shows the presence of a fifth and a seventh harmonic and no third; while the current in legs *X* and *Y* conforms to that required when a sine potential is applied across the two transformers connected in series.

OBSERVATIONS ON TRANSFORMERS IN ACTUAL SERVICE

To study the conditions found on transformers in actual service, an investigation was made of three transformers connected to the distributing mains of the Rochester Railway & Light Co., Rochester, N. Y. These transformers were rated 60-cycle, 150-kw., 2,400/4,150 Y-volt primary, 480-volt secondary and are similar in their general characteristics to the 25-cycle, 25-kw., 2,300-volt primary, 460-volt secondary transformers previously discussed. The connections to these transformers and the general arrangement of feeders, generators, etc., forming the distributing system are shown in Fig. 34. Transformers are located in substation No. 34, and it will be noted that power is supplied to this substation from alternators in generating stations Nos. 3, 5 and 15, connected in parallel. The following list gives the generators and their prime movers in the different generating stations.

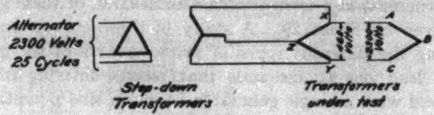


FIG. 33

GENERATING STATION NO. 3

Generators				Prime movers
No. of	Poles	Capacity kilowatts	Speed rev. per min.	
3*	80	1360	90	Reciprocating engine.
1	10	3000	720	Steam turbine.
1	24	2100	300	25-cycle induction motor.
2*	16	350	450	Water wheel.

* Originally two-phase, now three-phase T-connected.

GENERATING STATION NO. 5

Generators				Prime movers
No. of	Poles	Capacity kilowatts	Speed rev. per min.	
3	22	1200	327	Water wheels.
1*	16	350	450	Water wheels.
1	24	2100	300	25-cycle induction motor.

GENERATING STATION NO. 15

Generators				Prime movers
No. of	Poles	Capacity kilowatts	Speed rev. per min.	
2	36	500	200	Water wheel.

Oscillograms of the potential wave shape at no load across the terminals, and from terminal to neutral, of these generators are given on Sheet 29. A study of these curves and the list showing the different types of prime movers of the generators would lead one to conclude that results differing from those observed with a single generator having a sine potential should be expected.

Table 14 gives root-mean-square values of potential, current, and watts, taken as before.

TABLE 14.

Single-phase, core type, 60 cycle, 150-kw, 2400/4150 Y-volt primary, 480 volt secondary

	Voltage across				Current in line					Watts
	Lines	Leg	Delta	Neutral	A	B	C	Delta	Neutral	
(1)	4250	2705	720	1041	1.1	1.11	1.08	—	—	941
(2)	4342	2540	—	—	38.8	40.6	39.1	180	122	3467
(3)	4233	2453	73	—	1.35	2.0	1.6	—	1.45	1012
(4)	4293	2422	—	125	1.26	1.28	1.06	2.35	—	1025

(1) Open delta—isolated neutral.
(2) Closed delta—connected neutral.
(3) Open delta—connected neutral.
(4) Closed delta—isolated neutral.

It should be stated, that these figures could not be as accurately taken as those given in previous tables because of the fluctuations or variations consequent to the varying load of the system.

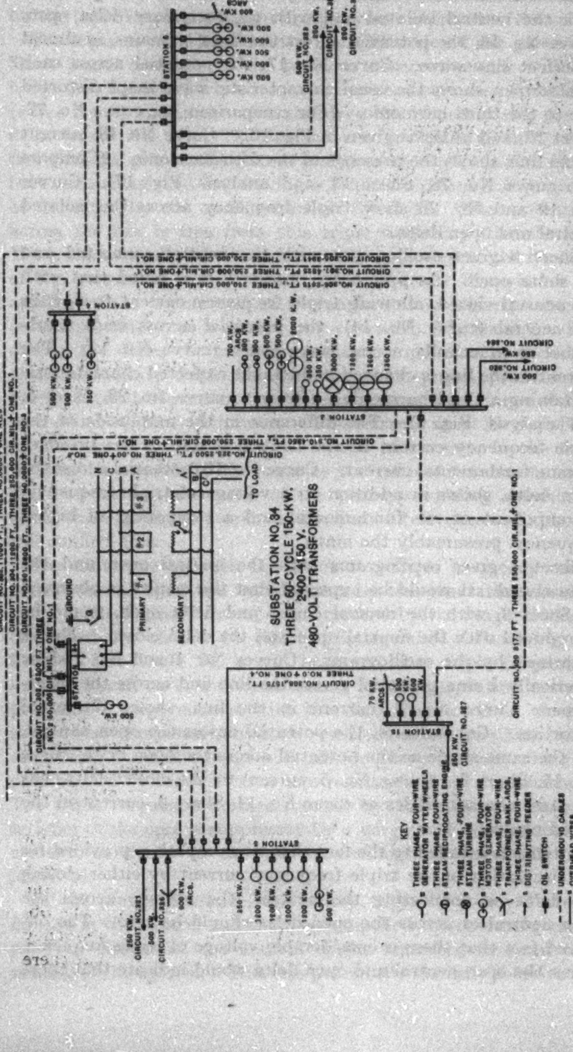

STATION 2
STATION 3
STATION 4
STATION 5
STATION 6
STATION 15
SUBSTATION NO.34
THREE 60-CYCLE 150-KW.
2400-4150 Y.
480-VOLT TRANSFORMERS
PRIMARY
SECONDARY
GROUND
TO LOAD
KEY
THREE PHASE, FOUR-WIRE GENERATOR WATER WHEELS
THREE PHASE, FOUR-WIRE STEAM RECIPROCATING ENGINE
THREE PHASE, FOUR-WIRE STEAM TURBINE
THREE PHASE, FOUR-WIRE MOTOR GENERATOR
THREE PHASE, FOUR-WIRE TRANSFORMER BANK ARCS
THREE PHASE, FOUR-WIRE DISTRIBUTING FEEDER
OIL SWITCH
UNDERGROUND CABLES
OVERHEAD WIRES

FIG. 34.—Electrical apparatus, the lines and distributing feeders on 4150-volt three-phase system Rochester Railway and Light Company, Rochester, N. Y.

Sheet 4 shows the usual oscillograms of current and potential with the neutral isolated and with the secondary delta open. Curve No. 16, the potential across the lines or mains, is almost a perfect sine wave. Curve No. 17, the potential across each transformer, shows the usual characteristic wave shape distorted due to the third harmonic. (For comparison, see curve No. 77, Sheet 13, and analysis given in Fig. 16.) Curve No. 18, current in the line, shows the presence of the fifth harmonic. (Compare also curve No. 78, Sheet 13, and analysis, Fig. 17). Curves No. 19 and No. 20 show triple frequency across the isolated neutral and open delta.

Sheet 3 gives oscillograms with the neutral connected and the delta open. As previously observed, it is noted that with the neutral closed, allowing triple frequency current to flow in the neutral (curve No. 14), the potential across each transformer is practically a sine wave shape (curve No. 12). The current in the line is changed and has the expected characteristic containing a third harmonic. (Refer to curve No. 23, Sheet 5, and analysis, Fig. 6). The difference in the amplitude of the triple frequency current in the neutral is due to the presence of some fundamental current. Curve No. 15, potential across the open delta, shows in addition to a voltage of triple frequency, a component of the fundamental and a component of higher frequency, presumably the ninth.

Sheet 1 gives oscillograms with the neutral open and the delta closed. It would be expected that the results as observed on Sheet 3, with the neutral closed and delta open, would be reproduced with the neutral open and the delta closed. This is confirmed by the oscillograms. Curves No. 1 and No. 2 show practically a sine potential across the line and across the transformer. Curve No. 3, current in the line, shows the usual distortion. Curve No. 4, the potential across the open neutral, has the same shape as the potential across the open delta, curve No. 15, Sheet 3. Curve No. 5, current in the closed delta, has the same characteristics as curve No. 14, Sheet 3, current in the closed neutral.

Attention is called to the fact that when a path is provided for the circulation of the triple frequency current by either closing the delta or connecting the neutral, the voltage across the open neutral or across the open delta should be zero. The observed fact that there is considerable voltage of triple frequency across the open neutral and open delta would indicate that there is some disturbance on the system which cannot be overcome by the triple frequency magnetizing current supplied to the core.

Oscillograms with both neutral and delta closed are given on Sheet 2 and contrary to the previous observations, it will be noted that a marked triple frequency current is present in the line (curve No. 8) and in the neutral (curve No. 9) and in the closed delta (curve No. 10). The explanation for this is given by the fact that the generating system produces an electromotive force between neutral and line having a triple frequency component, as indicated by the oscillograms on Sheet 29. The potential across the line is free from this triple frequency disturbance. When the neutral of the transformers is connected to the neutral of the generating system, this triple frequency disturbance is applied to the primary of each transformer and is reproduced on the secondary, as evidenced by curve No. 15, Sheet 3. By closing the delta, the triple frequency components in each leg of the secondary delta, being in the same phase, produce an energy current dependent on the resistance and reactance of the mains and of the transformers. This current must be supplied by the primary winding and the ratio of currents in the two windings is practically the same as the ratio of transformation. The current in the neutral of the primary winding should be about three times the current in the line. Reference to Table 14 will confirm this.

The difference between the effect of a triple frequency component forced upon the transformers by the generating system and a triple frequency component created by the magnetization characteristics should be clearly distinguished. Referring to Sheet 3 and Table 14, it will be noted that triple frequency voltage forced upon the transformers by the generating system produced a large current with the delta connected or closed, since these components of each transformer are in phase with each other. Small voltage will call for heavy current, which is only limited by the resistance and reactance of the transformer. The triple frequency voltage created by the magnetic characteristics of the core is suppressed by a very small demagnetizing current, as shown in the various oscillograms previously referred to.

In the present instance, this heavy triple frequency current flowing in the neutral and the line compelled the operating company to disconnect the neutral of the transformers from the neutral of the system. This was practically the only solution to the difficulty without disturbing the whole distributing system. Another solution of the difficulty would have been to use transformers delta-Y connected across each generator, using the neutral of the Y connection for the neutral of the general distributing system.

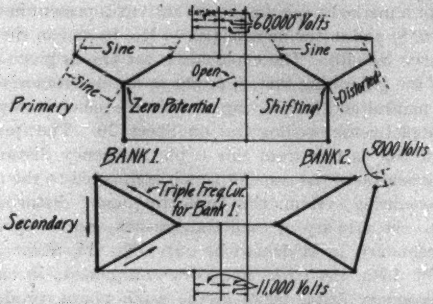

60,000 Volts
Sine
Sine
Sine
Open
Distorted
Primary
Zero Potential
Shifting
BANK 1.
BANK 2.
5000 Volts
Triple Freq. Cur. for Bank 1.
Secondary
11,000 Volts

Fig. 35a.—Diagram showing distribution of triple frequency current and voltage in parallel banks of single-phase transformers

As an important example of the confusing conditions occurring in practice resulting from potential wave distortion, the following case may be cited:

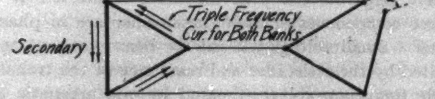

Sine
Sine
Sine
Closed
Sine
Primary
Zero Potential
Zero Potential
0 Volts
Triple Frequency Cur. for Both Banks
Secondary

Fig. 35b.—Diagram showing distribution of triple frequency current and voltage in parallel banks of single-phase transformers

Figs. 35*a*, *b*, *c*, *d*, represents two parallel banks of transformers with 60,000-volt Y primary and 11,000-volt delta secondary.

Occasion arose in which it was necessary to disconnect one of the transformers in bank No. 2. In replacing it and attempting to "phase out" the connections, 5,000 volts were measured across the open delta, indicating a very unbalanced condition. A study of the conditions existing will show that this should have been expected. With the neutrals of the two banks isolated and the delta of bank No. 2 open and that of bank No. 1 closed, a sine potential wave shape is maintained across the transformers of bank No. 1 by the triple frequency current supplied by the closed delta. The neutral of this bank should be at zero potential with respect to the ground.

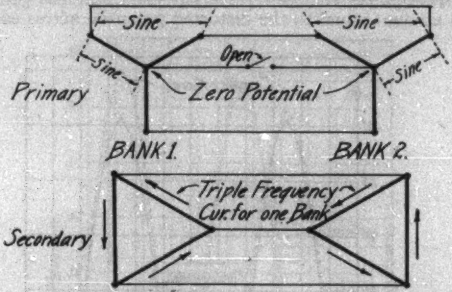

Sine
Sine
Open
Sine
Sine
Primary
Zero Potential
BANK 1.
BANK 2.
Triple Frequency
Cur. for one Bank
Secondary

FIG. 35C.—Diagram showing distribution of triple frequency current and voltage in parallel banks of single-phase transformers

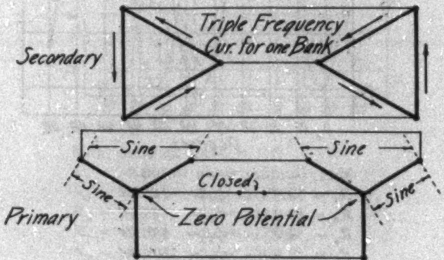
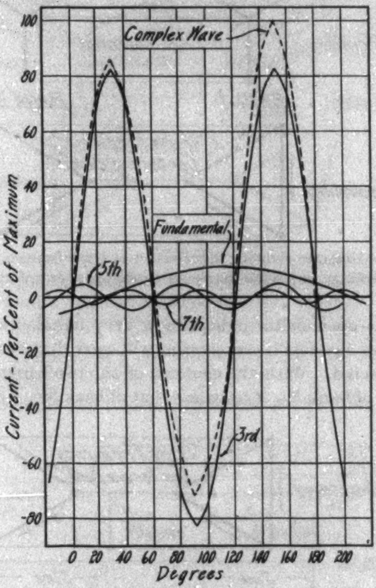

Triple Frequency
Cur. for one Bank
Secondary
Sine
Sine
Closed
Sine
Sine
Primary
Zero Potential

FIG. 35D.—Diagram showing distribution of triple frequency current and voltage in parallel banks of single-phase transformers

With the neutral of bank No. 2 open, while the potential across the 60,000-volt line may be a sine shape, no provision is made to insure a sine potential across each transformer, and consequently the two banks are unbalanced across the neutrals by an amount equal to the distorted potential across each leg of bank No. 2; *i.e.*, the neutral shifts and there is an unbalancing of voltage across the open delta of bank No. 2.



Max. complex wave = 100

$R_1 = 10.8$ $\phi_1 = -24° 36'$

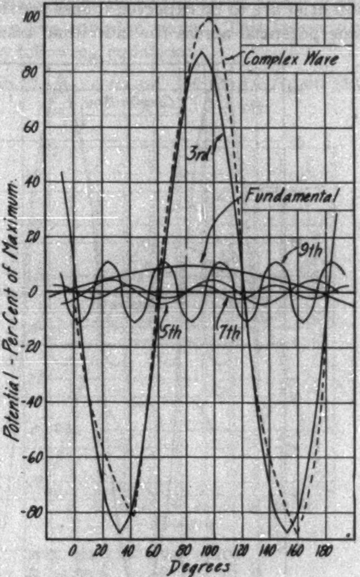
$R_3 = 82.9$ $\phi_3 = -2° 11'$

$R_5 = 4.9$ $\phi_5 = 48° 19'$

$R_7 = 2.6$ $\phi_7 = 150° 58'$

FIG. 36.—Analysis of oscillogram No. 74 sheet No. 12

By connecting the neutrals, all triple frequency disturbances disappear and sine potential is applied to the transformers of both banks, the necessary triple frequency current being supplied for both banks by the closed delta of bank No. 1. Upon closing the delta of bank No. 2, the voltage now read across the open delta will be zero, and the secondary windings of both banks will equally contribute the necessary triple frequency currents to maintain sine potential across the transformers of both banks. Under such conditions, the connection between the neutrals of the primaries of the two banks may be open or disconnected entirely without any disturbance or change in the potential wave shape applied to the transformers.

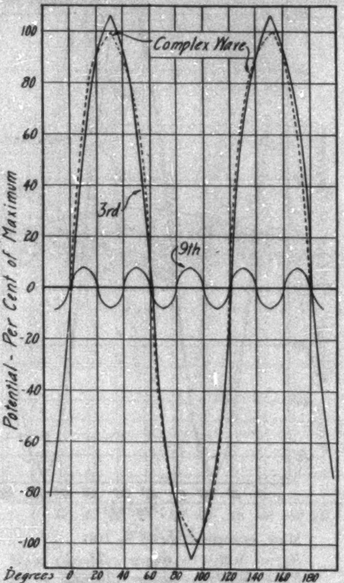


Max. complex wave = 100
$R_1 = 9.2$ $\phi_1 = 7° \; 1'$
$R_3 = 87.7$ $\phi_3 = 172° \; 32'$
$R_5 = 4.4$ $\phi_5 = -44° \; 3'$
$R_7 = 2.3$ $\phi_7 = 177° \; 43'$
$R_9 = 11.2$ $\phi_9 = 236° \; 8'$

FIG. 37.—Analysis of oscillogram No. 75 sheet No. 12

It is evident that the investigation and observations of the distribution of current and potential has great practical value.

The broadest general conclusion to be drawn from the observations presented in this paper, so far as they relate to transformers, is that in any distributing system disturbances of current and potential are to be expected unless provision is made to maintain sine potential across the individual transformers.



Max. complex wave = 100
$R_3 = 106.0$ $\phi_3 = -2° 26'$
$R_9 = 8.1$ $\phi_9 = 3° 9'$

FIG. 38.—Analysis of oscillogram No. 79 sheet No. 13

The writer takes this opportunity to acknowledge assistance in the discussion and analysis of the curves to Mr. W. W. Lewis.

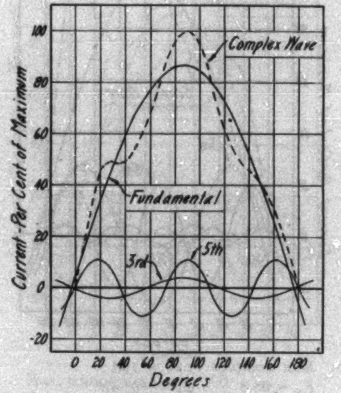
APPENDIX

The analysis of the waves in the foregoing article was carried on by the method of Professor S. P. Thompson, as given in Vol. II of his work on Dynamo Electric Machinery. A brief outline of the method may be of interest.

The following fundamental assumptions are made:

1. Any periodic complex wave, according to the theorem of Fourier, may be considered as built up of a series of harmonic terms, the fundamental one of the series being of the same frequency as the given complex wave. This theorem may be expressed by the following equation:

$$y = R_1 \sin(\theta+\phi_1) + R_3 \sin(3\theta+\phi_3) + R_5 \sin(5\theta+\phi_5) \quad \textbf{(A)}$$
$$+ \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; \text{etc.}$$



Max. complex wave = 100

$R_1 = 86.8$ $\phi_1 = 3° \; 6'$

$R_3 = 3.6$ $\phi_3 = 189° \; 46'$

$R_5 = 11.1$ $\phi_5 = 1° \; 14'$

FIG. 39.—Analysis of oscillogram No. 83 sheet No. 14

where R_1, R_3, etc., are the amplitudes of the harmonics, and ϕ_1, ϕ_3, etc., are the angles of lag with respect to the zero of the complex wave.

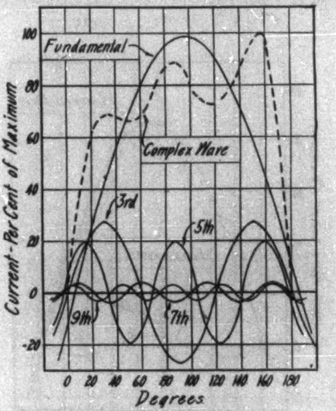
2. As indicated by equation (**A**), only odd harmonics are present, a well-known characteristic of alternator waves.

3. The lagging harmonics in equation (**A**) may be resolved into two components; one a sine curve with zero lag and the other a sine curve with a lag of 90 degs.; in other words, a sine curve in

phase with the complex wave and a cosine curve. Equation **(A)** may then be written

$$y = A_1 \sin\theta + B_1 \cos\theta + A_3 \sin 3\theta + B_3 \cos 3\theta + A_5 \sin 5\theta + B_5 \cos 5\theta + \ldots \ldots \text{etc.} \quad \textbf{(B)}$$

4. The mean horizontal axis of the curve is midway between the highest and lowest points of the curve, and the origin or zero point of the complex wave may be chosen where this curve crosses the horizontal axis.



Max. complex wave = 100

$R_1 = 98.8$ $\phi_1 = -5° 43'$

$R_3 = 27.2$ $\phi_3 = -1° 13'$

$R_5 = 19.9$ $\phi_5 = 15° 32'$

$R_7 = 3.7$ $\phi_7 = 29° 51'$

$R_9 = 3.1$ $\phi_9 = 48° 22'$

FIG. 40.—Analysis of oscillogram No. 84 sheet No. 14

5. The positive and negative portions of the waves under consideration are identical, so that only a half-wave, *i.e.*, 180 degs. need be considered.

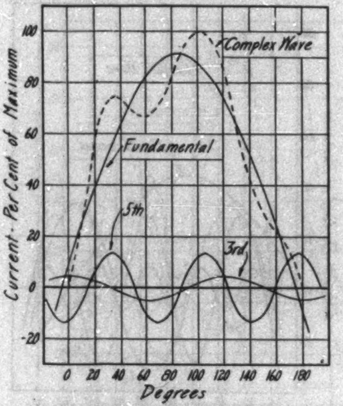
6. If the half-wave is symmetrical to the right and left of 90 degs., only sine terms are present. If not symmetrical in this respect, both sine and cosine terms are present. The latter is the usual case and in general need be the only one considered.

The problem is to find the unknown coefficients A_1, A_3, A_5, etc., and B_1, B_3, B_5, etc. These may then be combined to find R_1, R_3, R_5, etc., by the equation

$$R_1 = \sqrt{A_1^2 + B_1^2} \tag{C}$$

and the angles ϕ_1, ϕ_3, ϕ_5, etc., by the equation

$$\phi_1 = \tan^{-1} \frac{B_1}{A_1} \tag{D}$$



Max. complex wave = 100

R_1 = 91.0 ϕ_1 = 5° 22′

R_3 = 4.5 ϕ_3 = 83° 58′

R_5 = 13.7 ϕ_5 = 73° 20′

R_7 = 2.6 ϕ_7 = 238° 24′

FIG. 41.—Analysis of oscillogram No. 85 sheet No. 14

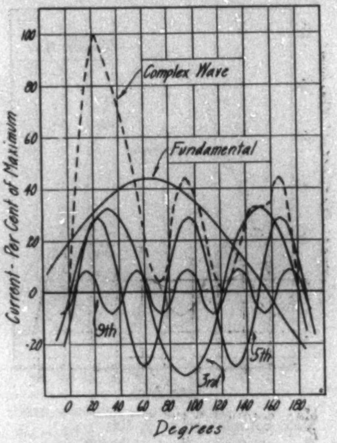
Consider that only the first three harmonics in the series are required, *i.e.*, fundamental, third and fifth. We must then find six unknowns, *viz.*, A_1, A_3, A_5, and B_1, B_3, B_5, and consequently must have six equations. If sine terms only were present, we might choose three convenient points on the wave whose ordinates would then satisfy the following equations:

$$\begin{aligned} y_1 &= A_1 \sin \theta_1 + A_3 \sin 3\,\theta_1 + A_5 \sin 5\,\theta_1 \\ y_2 &= A_1 \sin \theta_2 + A_3 \sin 3\,\theta_2 + A_5 \sin 5\,\theta_2 \\ y_3 &= A_1 \sin \theta_3 + A_3 \sin 3\,\theta_3 + A_5 \sin 5\,\theta_3 \end{aligned} \tag{E}$$

which equations may be solved simultaneously for A_1, A_3 and A_5. Similarly, if cosine terms only were present, three other equations might be formed, *viz.*,

$$\begin{aligned} y_0 &= B_1 \cos \theta_1 + B_3 \cos 3\,\theta_1 + B_5 \cos 5\,\theta_1 \\ y_1 &= B_1 \cos \theta_2 + B_3 \cos 3\,\theta_2 + B_5 \cos 5\,\theta_2 \\ y_2 &= B_1 \cos \theta_3 + B_3 \cos 3\,\theta_3 + B_5 \cos 5\,\theta_3 \end{aligned} \qquad \textbf{(F)}$$

and solved simultaneously for B_1, B_3, B_5. If both sine and cosine terms are present, then each ordinate chosen is made up of two portions, the ordinate of the sine component and the ordinate of the cosine component of the wave at that point, and their separation may be accomplished as follows:



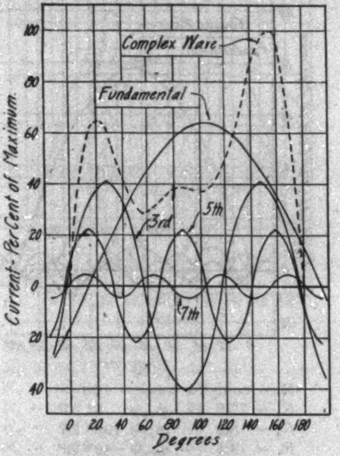
Max. complex wave = 100
$R_1 = 43.8$ $\phi_1 = 25° 50'$
$R_3 = 32.4$ $\phi_3 = -2° 40'$
$R_5 = 28.7$ $\phi_5 = -26° 45'$
$R_9 = 8.5$ $\phi_9 = 35° 11'$

FIG. 42.—Analysis of oscillogram No. 91 sheet No. 15

It is known that $\sin \theta = \sin (180° - \theta)$ and that $\cos \theta = -\cos (180° - \theta)$. Take an ordinate y_θ (θ less the 90°) and an ordinate $y_{(180°-\theta)}$. If we add these ordinates, any component parts due to $\cos \theta$, $\cos 3\,\theta$, $\cos 5\,\theta$, etc., will cancel while any component parts due to $\sin \theta$, $\sin 3\,\theta$, $\sin 5\,\theta$, etc., will be doubled. If we subtract $y_{(180°-\theta)}$ from y_θ, the sine components will cancel, leaving the doubled cosine components. That is, expressed algebraically,

$$\left.\begin{aligned} s_1 &= y_\theta + y_{180°-\theta} = 2\,(A_1 \sin \theta_1 + A_3 \sin 3\,\theta_1 + A_5 \sin 5\,\theta_1) \\ d_1 &= y_\theta - y_{180°-\theta} = 2\,(B_1 \cos \theta_1 + B_3 \cos 3\,\theta_1 + B_5 \cos 5\,\theta_1) \end{aligned}\right\} \quad \text{(G)}$$

We may thus find a number of ordinates, $\frac{s_1}{2}$, $\frac{s_2}{2}$, $\frac{s_3}{2}$, which may be substituted for y_1, y_2, y_3, in equation (**E**) and a similar set of ordinates $\frac{d_1}{2}$, $\frac{d_2}{2}$, $\frac{d_3}{2}$, which may be substituted for y_0, y_1, y_2, in equation (**F**), and equations (**E**) and (**F**) solved simultaneously for A_1, A_3, A_5, and B_1, B_3, B_5. The amplitudes R_1, R_3, R_5, and angles ϕ_1, ϕ_3, ϕ_5, may then be found from equations (**C**) and (**D**).



Max. complex wave = 100

$R_1 = 63.9$ $\phi_1 = -14° \, 0'$

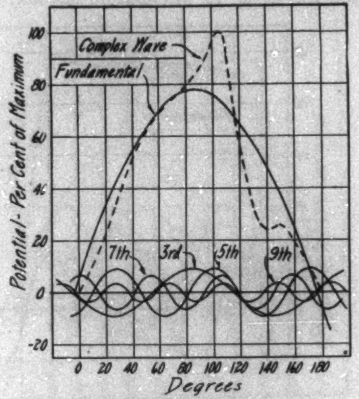
$R_3 = 41.0$ $\phi_3 = 8° \, 28'$

$R_5 = 22.1$ $\phi_5 = 21° \, 54'$

$R_7 = 4.8$ $\phi_7 = 10° \, 11'$

FIG. 43.—Analysis of oscillogram No. 97 sheet No. 16

It is apparent that if we consider the complex wave to be made up of a fundamental, third, and fifth harmonics, and there also happens to be a seventh or other higher harmonic present, the amplitudes that we find on the assumption that the first three harmonics only are present, will each contain a portion of the amplitudes belonging to the seventh and higher harmonics, and the analysis is an approximation to that extent. Therefore, the more harmonics for which we strive, the more accurate will be the analysis, also the more complicated the simultaneous equations to be handled. An analysis for all the harmonics up to and including the eleventh is sufficiently accurate for nearly all cases and requires the handling of six simultaneous equations, which is about as many as it is practicable to deal with. For this purpose, the quarter-wave is divided into six intervals of 15 deg. each and the ordinates measured by means of a dividing engine. These ordinates are combined with the ordinates of the supplementary angles in the second quarter of the wave, giving the sums s_1, s_2, etc., and the differences d_1, d_2, etc., to be substituted



Max. complex wave = 100

$R_1 = 77.9 \qquad \phi_1 = 3° 57'$

$R_3 = 8.9 \qquad \phi_3 = 195° 26'$

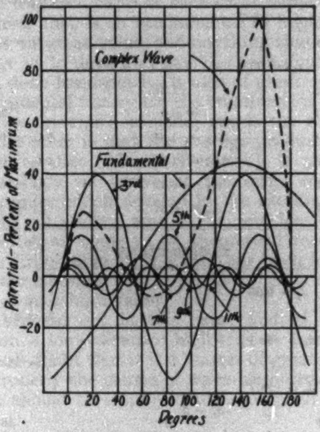
$R_5 = 9.1 \qquad \phi_5 = -49° 39'$

$R_7 = 6.9 \qquad \phi_7 = 78° 55'$

$R_9 = 3.6 \qquad \phi_9 = 203° 28'$

FIG. 44.—Analysis of oscillogram No. 99 sheet No. 17

in the proper equations. By means of a schedule prepared by Professor Thompson and slightly modified for our use, the solution of the simultaneous equations is greatly facilitated. The complete analysis of curve No. 78, Sheet 13, shown in detail in Fig. 17, is appended to show the use of this schedule



Max. complex wave = 100
$R_1 = 44.1$ $\phi_1 = -48^\circ\ 59'$
$R_3 = 39.8$ $\phi_3 = 16^\circ\ 42'$
$R_5 = 16.2$ $\phi_5 = 33^\circ\ 21'$
$R_7 = 7.11$ $\phi_7 = 49^\circ\ 49'$
$R_9 = 4.76$ $\phi_9 = 61^\circ\ 29'$
$R_{11} = 3.48$ $\phi_{11} = 74^\circ\ 36'$

FIG. 45.—Analysis of oscillogram No. 128 sheet No. 22

SCHEDULE FOR THE ANALYSIS OF A PERIODIC CURVE IN WHICH APPEAR ONLY ODD HARMONICS UP TO THE ELEVENTH

(1)	1	2	3	4	5	6
	$y_1 = 7.6$ $y_{11} = 37.3$	$y_2 = 11.2$ $y_{10} = 78.8$	$y_3 = 24.0$ $y_9 = 86.4$	$y_4 = 65.0$ $y_8 = 65.0$	$y_5 = 96.1$ $y_7 = 61.8$	$y_6 = 90.0$
Sum	44.9	90.0	110.4	130.0	157.9	90.0
Dif.	-29.7	-67.6	-62.4	0.0	34.3	
(2)	$s_1+s_3-s_5$		s_2-s_6		$d_1-d_3-d_5$	
	44.9 110.4		90.0 -90.0		29.7 34.3	
	155.3 -157.9				-64.0 62.4	
	$r_1 = -2.6$		$r_2 = 0.0$		$e_1 = -1.6$	

(3) SINE TERMS

Sine	1st and 11th		3rd and 9th		5th and 7th	
0.262	$s_1 = 11.8$				$s_5 = 41.4$	
0.500		$s_2 = 45.0$				$s_2 = 45.0$
0.707	$s_3 = 78.2$		$r_1 = 1.84$		$-s_3 = 78.2$	
0.866		$s_4 = 112.7$				$-s_4 = 112.7$
0.966	$s_5 = 152.3$				$s_1 = 43.4$	
1.000		$s_6 = 90.0$		$r_2 = 0.0$		$s_6 = 90.0$
1st col.	242.3		−1.84		6.6	
2nd col.	247.7		0.0		22.3	
Sum	$6A_1 = 490.0$		$6A_3 = -1.84$		$6A_5 = 28.9$	
Diff.	$6A_{11} = -5.4$		$6A_9 = -1.84$		$6A_7 = -15.7$	
	$A_1 = 81.7$		$A_3 = 0.31$		$A_5 = 4.8$	
	$A_{11} = 0.9$		$A_9 = -0.31$		$A_7 = -2.6$	

COSINE TERMS

0.262		$d_5 = 9.00$				$d_1 = -7.79$
0.500	$d_4 = 0$				$d_4 = 0$	
0.707		$d_3 = -44.1$		$e_1 = -1.13$		$-d_3 = 44.1$
0.866	$d_2 = -58.6$				$-d_2 = 58.6$	
0.966		$d_1 = -28.7$				$d_5 = 33.2$
1.000			$-d_4 = 0$			
1st col	−58.6		0		58.6	
2nd col.	−63.8		−1.13		69.5	
Sum	$6B_1 = -122.4$		$6R_3 = -1.13$		$6B_5 = 128.1$	
Diff.	$6B_{11} = 5.2$		$6B_9 = 1.13$		$6B_7 = -10.9$	
	$B_1 = -20.4$		$B_3 = -0.19$		$B_5 = 21.4$	
	$B_{11} = 0.9$		$B_9 = 0.19$		$B_7 = -1.8$	

(4) $R_1 = \sqrt{81.7^2 + 20.4^2} = 84.2$ $\tan \phi_1 = \frac{-20.4}{81.7} = -0.25$

$R_3 = \sqrt{0.31^2 + 0.19^2} =$ negligible $\tan \phi_3 = \quad =$

$R_5 = \sqrt{4.8^2 + 21.4^2} = 21.9$ $\tan \phi_5 = \frac{21.4}{4.8} = 4.46$

$R_7 = \sqrt{2.6^2 + 1.8^2} = 3.2$ $\tan. \phi_7 = \frac{-1.8}{-2.6} = 0.693$

$R_9 = \sqrt{0.31^2 + 0.19^2} =$ negligible $\tan \phi_9 = \quad =$

$R_{11} = \sqrt{0.9^2 + 0.9^2} =$ negligible $\tan \phi_{11} = \quad =$

$\phi_1 = 14° 2$ $\phi_7 = 214° 43'$

$\phi_3 =$ $\phi_9 =$

$\phi_5 = 77° 21'$ $\phi_{11} =$

DISCUSSION ON "OBSERVATION OF HARMONICS IN CURRENT AND IN VOLTAGE WAVE SHAPES OF TRANSFORMERS", SAN FRANCISCO, CAL., MAY 6, 1910.

H. J. Ryan: I don't know that there is anything I can add in an effective way to a paper of such great value. Any knowledge of anything that is so fundamental in engineering as the transformer, is of great value, and anything that tends to bring that knowledge up to date, and that has been done in this paper and has been done handsomely, is also of great value.

In the fundamental theory for the treatment of things of this kind use of two principles is made; one is the conservation of energy, and the other is that the average product of two alternating quantities that differ in frequency is zero. Thus by theoretical methods we arrive at the same conclusion, *viz.*, that the harmonics which develop in the exciting current of a transformer do not convey any of the core loss energy.

However, what we come to by theoretical reasoning is generally of very little value until a way has been found to check the result in the laboratory or in practice. It is right here that this paper is of such high value.

The facts brought out in this paper and in Mr. Faccioli's recent tests on a long distance high-tension transmission line show beyond all doubt that it is a matter of great importance to understand properly the causes of wave-form distortion and the methods that should be employed to accomplish their elimination.

We know that a 200-mile, 60-cycle, high-tension transmission line with its receiver circuit open delivers a terminal pressure that is considerably higher than the pressure at the source. With sine wave pressure at normal frequency applied at the source this terminal pressure rise will be a certain amount. Now assume the use of a non-sine wave source pressure made up of one part at normal frequency and a second part at ten per cent of the value of, and at a frequency of three times the first part, being different in frequency each of these pressure parts will work upon the line independently to produce a rise in the terminal pressure. The rise in value and shift in phase will be much greater in proportion for the third harmonics than the fundamental. The result will be to change and to distort greatly the wave form of the open circuit terminal pressure. There will be a corresponding increase in certain instantaneous values of the pressure accomplished by increase of the electric strain on the insulation and such other disorders as follow because of the use of the irregular wave forms.

Mr. Faccioli's transmission experiments and investigations have checked the above theoretical reasoning. It is, therefore, decidedly evident that all wave distortions introduced by three-phase source star-connected transformers, neutrals free, or by any other means should be carefully avoided in high-tension long distance transmission.

G. Faccioli: Professor Ryan brought out the point of the influence of harmonics on the core losses.

This is a very interesting problem. It is true that the high frequency component of the exciting current of a transformer is wattless, but I do not agree with the author of the paper in his conclusion that the distortion of the current is neither a cause nor an effect of the energy loss in the core.

The figures below are respectively a reproduction of Fig. 9 and Fig. 10. The straight line *a* is the loop obtained by plotting the values of the flux in function of the values of the wattless component of the fundamental of the exciting current. This condition of affairs would be possible if we used in the transformer core a material of constant high permeability. Curve *b* is obtained by taking as abscissæ the values of the fundamental and harmonics of the exciting current in phase with the flux. Both *a* and *b* presuppose no losses, but while *a* assumes constant permeability, *b* admits a change in permeability.

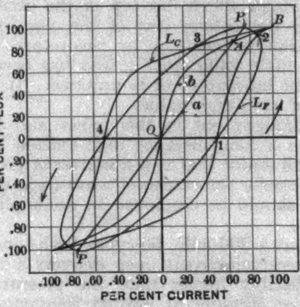


FIG. 9

It is interesting to note that the line *a* crosses the curve *b* in one point only, *A*. This means that if we increase the flux from zero to maximum positive in the case of constant permeability and no losses, the current should be a sine wave in phase with the flux. If the permeability is not constant, then while the flux increases from zero to the point corresponding to *A*, the values of the current are smaller than the values of the sine wave. From the point corresponding to *A* to the maximum value of the flux *B*, the current is higher than the values of the sine wave. Decreasing the flux from maximum positive to zero, we repeat the phenomenon in a reverse direction.

It follows that the change in permeability has caused the current to be less than the value of the sine wave for part of a half cycle; then for another part of a half cycle the current becomes higher than the values of the sine wave, and finally, for the rest of the half cycle, the current is again smaller than the sine values. It is apparent, therefore, that the distortion of current introduced by the change of permeability, crosses the zero line in two points during a half cycle, and is symmetrical with respect to a vertical axis drawn through the maximum value of the flux.

The change of permeability introduces then a high harmonic in the current, whose fundamental wave is of triple frequency. This does not mean that this extra current is a triple frequency sine wave, but it shows clearly, in my opinion, that the disturbance has a large triple frequency component, and is symmetrical with respect to the flux wave.

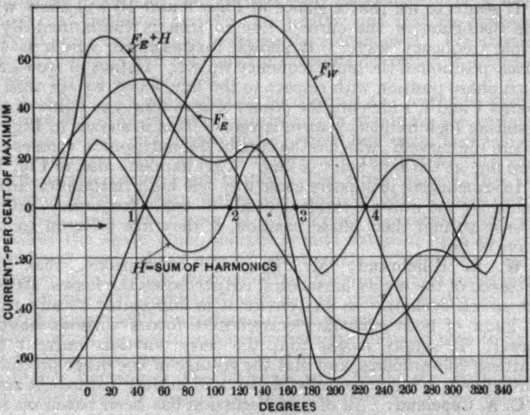


Fig. 10

If now, we take losses into consideration, the line *a* is expanded into an ellipse, and the curve *b* becomes the regular hysteresis loop.

Following the same reasoning as before, we see that in the first quarter cycle of the flux (while the flux grows from zero to maximum positive) the hysteresis loop, starting from point 1, crosses the ellipse at the point 2. It follows that from 1 to 2, the presence of the iron causes the current to be less than the values of the sine wave, (Fig. 10.) From 2 to 3, the current is larger than the sine values, and finally from 3 to 4, the extra current introduced by the iron has again negative values.

It follows immediately that the total distortion introduced by the iron, including losses, is fundamentally of triple frequency, as in the former case, where losses were neglected, but when losses are considered, the distortion is no longer symmetrical with respect to the vertical axis drawn through the maximum value of the flux, as shown by the unsymmetrical position of the points two and three.

We may therefore draw the conclusion that the presence of losses has modified the distortion of current, which would be introduced by a mere change of permeability. The high frequency components of the current are wattless for the whole cycle, but they are active in distributing the losses throughout the cycle, and part of the distortion is a consequence of the presence of these losses.

It seems to me that a glance at Figs. 9 and 10 will show why the distortion of the current due to iron is fundamentally a triple frequency wave. It shows, furthermore, which is the phase position of the high frequency waves. In fact, if we locate such phase position with respect to the flux wave, we see that at points 1 and 4, which are the points of zero flux, the value of the resulting high frequency wave is zero. This is shown in Fig. 10 where the curve *H*, which is the sum of the harmonics, crosses the zero line at the zero point of flux. This happens also in Fig. 12.

In conclusion, it appears clear why the high harmonics introduced by the iron are fundamentally of triple frequency, and it is easy to find their phase position, if they are referred to the wave of flux.

W. A. Hillebrand: Mr. Faccioli's conclusions, that the presence of the higher harmonics, redistributes the losses, strikes me as self-evident. In any circuit it is impossible at any time to know of both currents electromotive forces without having power. It simply means that the term wattless current for wattless volt-amperes, and that the voltage of the other products throughout, is fundamentally higher, and in that instance is zero.

C. A. Copeland: All of this discussion has been based on the assumption that we start out with a sine curve. It would be rather interesting to find out either theoretically or practically what are the worst conditions we would find by starting out with a curve which was a little flat topped or peaked. I was wondering whether there had been any oscillograms taken, starting out with either a flat top or peaked top wave, so as to show what the worst condition would be that we might have, under these conditions.

G. Faccioli: Of course, in a paper of this kind, it was necessary to apply sine waves to the transformers in order to obtain comparable results.

We can deduce the effect of the wave form on the triple frequency component of the exciting current by remembering that in a Y-connected system (neutral disconnected, secondary open) the electromotive force across each individual transformer is distorted as a consequence of the fact that triple frequency currents cannot flow in the Y.

Then, if we apply to a transformer an electromotive force, as the one represented, for instance, in curve 17, sheet 4, we must expect that this electromotive force will not call for a triple frequency exciting current. Now this electromotive force contains a triple frequency conponent itself. If we reverse this component 180 deg., we should expect to reach the conditions where the triple frequency exciting current will be maximum.

President Stillwell: I think it might be interesting if you would explain to what extent the use of the silicon steel affects the triple frequency current.

G. Faccioli: The new silicon steel has a hysteresis loop which is different from the loop of iron used previously. It is well known that the losses per cycle are smaller, and that the permeability at high densities is lower in the silicon steel. We should then naturally expect a somewhat different distortion of exciting current due to silicon steel.

C. L. Cory: It is interesting to contrast the methods which Professor Ryan used twenty years ago in obtaining the curves, point by point, not upon single waves but upon succeeding waves, using a 133-cycle generator, with the results that are shown in the paper read to-day. The three papers, that of Professor Ryan twenty years ago, that of Mr. Rhodes read yesterday, and this paper of Mr. Frank's presented to-day are all of the same type, and the results obtained from the experimental work done are of great value. The things that Professor Ryan really discovered are the things that have now been completely developed and are so clearly shown in the oscillograms so well reproduced in the paper.

From what we heard yesterday morning and also here to-day it is possible that we may conclude that the third harmonic and the higher harmonics, the fifth, seventh, ninth, etc., introduce only difficulties in connection with the generation and use of alternating currents. I do not believe that that conclusion necessarily follows. It was shown yesterday by Mr. Rhodes that the triple and higher harmonics are produced by generators under certain circumstances and this morning by Mr. Frank it has been shown that, no matter what kind of a curve we start with from the generator, somewhere in our transmission system we will find the conditions which are shown by these curves and we cannot avoid the distortion from the true sine wave.

The presence of the higher harmonics have been found troublesome and have almost always lead to difficulties. To-day in the transmission of power we are still using a relatively high frequency. From the beginning of the use of alternating currents the frequency has been reduced from 133 and 120 cycles down to 60, 50, 40 and even 25 cycles, and when we begin to transmit still larger quantities of power over distances three or four times as great as ordinarily found at the present, or up to 500 or 600 miles, perhaps lower frequencies such as 10 12½ or 15 cycles will be found, under certain circumstances to be decidedly preferable.

Is it not possible therefore as the art of the generation and application of electricity still further develops that we may generate by a single generator currents of more than one frequency, or, what would be equivalent, one current of two or more frequencies? We really produce such currents in the generators that were described by Mr. Rhodes, although we do not want them, and as shown by Professor Bedell greater economy of copper results when two currents of differing frequencies are transmitted over the same conductor, and ultimately we may to advantage make use of the combination for more efficiently transmitting power than is possible using current of only one frequency in each conductor.

Silvanus P. Thompson (by letter): Mr. Frank's paper is of particular interest to me, because I happen to have just prepared for the Physical Society of London a yet unpublished note on Hysteresis Loops and Lissajous Figures, the substance of which is as follows. Just as any wave curve, whether of current or of voltage, can be analyzed according to Fourier's theorem into a harmonic series of sine and cosine terms containing only odd terms in the series, so any hysteresis loop can be analyzed into a harmonic series of Lissajous figures, (in sine and cosine terms) containing only odd terms in the series.

The area of the hysteresis loop represents the energy spent in a cycle of magnetizing operations. If we represent the impressed electromotive force as a sine-function of the time, it is known that the wave-form of the flux will be a pure cosine function of the time, and that the wave-form of the reactive electromotive force will be a pure (negative) sine function of the time. Now, if there are present hysteresis and eddy-currents, the current curve will, as known ever since Ryan's classical researches of 1890, not have a simple wave form. It may contain terms of the following orders:

1. $A_1 \sin p t$
2. $B_1 \cos p t$
3. $A_3 \sin 3 p t$
4. $B_3 \cos 3 p t$
5. $A_5 \sin 5 p t$
6. $B_5 \cos 5 p t$

with possibly other terms of higher orders. Now as the impressed voltage has a form expressed by $V_1 \sin p t$, the total energy expended in a cycle will be represented by the result of multiplying $V_1 \sin p t$ into each of the above terms, and integrating each such product around a whole cycle, or from $t = 0°$ to $T = 360°$. But, as is well known, the following integrals all have zero value if integrated over a whole period:

$$\int \sin pt \cos pt,$$

$$\int \sin pt \sin n\, pt$$

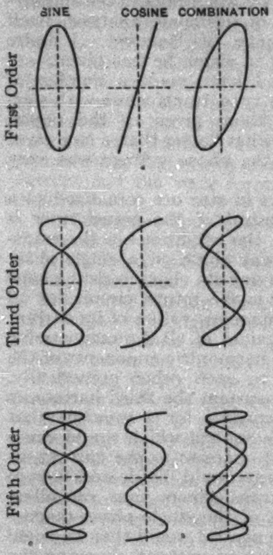
$$\int \sin pt \cos n\, pt;$$

where *n* is any whole number. The only product that remains is therefore the fundamental, *viz*:—

$$\int_0^T \sin^2 pt$$

That is to say the only component which involves the expenditure of any energy in the cycle is the sine-component of the first order; that is so much of the current wave as in phase with the impressed voltage. All other components may distort the form of the current wave, and therefore of the hysteresis loop, but alter the amount of the area of the loop in nowise. The area of the loop is equivalent under all cases to that of an ellipse, the principal axes of which are respectively the maximum flux-density the value of $\mathcal{H}$ due to the maximum value of the first-order sine component of the current curve.

The effect of magnetic leakage, or of an air-gap in the iron core is to shear over the hysteresis loop, that is to introduce as a component a first-order cosine term.



The above are the Lissajous figures which correspond to the several terms:

The total areas of Lissajous figures, of all orders except the first is zero; their negative and positive portions being always equal.

Eddy currents will invariably give sine-components of the first order, and add a further elliptical component to the ellipse. Eddy-currents of the third order, which will be present only if there are third order components in the voltage curve, will tend to distort in the form containing both sine and cosine components of the third order, resembling the letter S.

The ordinary hysteresis loops with acute peaked forms at their ends, obtained when the flux-density is pushed to high values, contain negative cosine terms of third, fifth, and higher orders, and cannot be adequately represented without going to terms higher than the eleventh.

I am able to confirm Mr. Frank's conclusion that the distortion of the form of the current wave curve is neither a cause nor an effect of energy loss in the core, but depends only on the variations of the permeability of the steel.

May I be allowed in conclusion to express my gratification that so much utility has been found by Mr. Frank in the employment of my arithmetical method of harmonic analysis, itself derived from that of Professor Runge of Hanover. I desire to thank him for the exposition of it which he has given.

Edmund C. Stone (by letter): I have made a number of oscillograms on a three-phase core type transformer with star-connected primary, which check those given in the paper. The wave form impressed was somewhat flatter than a sine wave and the effect of this in peaking the phase voltage was very marked.

If three single-phase transformers in star are connected to a three-phase generator and the neutral of the transformer is connected to that of the generator, the conditions in the transformers are the same as if each was alone on a single-phase circuit; the magnetizing current having its characteristic shape in each transformer. The neutral is the return circuit for all the transformers, so that the instantaneous values of its current are the sum of the instantaneous values of all the magnetizing currents. It carries all of the third harmonic components of the single-phase currents, which add to each other numerically, since in a symmetrical three-phase system the third harmonics all have the same phase. Now imagine for a moment that an e.m.f. could be impressed on the neutral which would cause a current to flow exactly equal and opposite to the current already in the neutral. Such a current would divide and flow in the same direction through the transformers thus cancelling out the third harmonic component of the single-phase magnetizing currents. The current in the neutral would then be equal to zero and the neutral could be opened without changing the conditions in any way. Hence it will be seen that when the transformers are star connected with the neutral open, a current of triple frequency is present in each one which is of the same phase in all three transformers and is *subtracted* from the single-phase magnetizing current, thereby eliminating from the latter its third harmonic. This current, of course, sets up a flux of triple frequency and same phase in all the cores, which subtracts from the single-phase flux and introduces a third harmonic into the counter e.m.f. wave accordingly. Such a third harmonic increases the maximum value of the phase e.m.f. but does not appear at the terminals of the star-connected windings. When the secondaries are connected in series or delta, however, the triple frequency components of voltage are in phase and add to one another, thus producing an unbalanced e.m.f. around the delta. When the delta is closed this voltage becomes practically zero and a current flows which is equal to that producing it; that is the third harmonic of the single-phase magnetizing current has been transferred from the primary where it cannot flow, to the secondary where it can flow through the closed delta.

In the case of three single-phase transformers, the flux set up by the triple frequency component of magnetizing current has the same circuit as the main flux, that is, the core of the transformer, which being of exceedingly low reluctance, permits considerable flux to be set up, thus causing great distortion to the wave form of the phase e.m.f. (as shown by sheet No. 13). In the case of the three-phase core type transformer, however, this triple frequency flux cannot pass around the main circuit, since it would then be opposed by the flux of another phase. The result is that it must find a return path through air or the case and end frames. This local circuit has necessarily a high reluctance so that only a small flux is set up by the third harmonic current and the wave form of the phase e.m.f. is only slightly distorted.

C. Fortescue (by letter): This paper shows very clearly the necessity of considering the wave forms of generator e.m.fs. of transformer exciting currents, etc., with reference to their effect in polyphase circuits.

The writer, during the past few years, has been frequently called upon to explain phenomena due to such causes and many of his conclusions are corroborated by the data given in Mr. Frank's paper and his explanation of them.

Referring to Mr. Frank's discussion of interconnected transformers: it is shown that if the third harmonic component of the exciting current is prevented from flowing by the method of connecting the transformers a third harmonic component of e.m.f. will appear in the transformer windings, which will increase the insulation stress throughout the transformer. It may be well to remark that the effect would not be so marked in ordinary commercial transformers as for the case given, since the iron is not usually run at so high a density as 90 kilo-lines per square inch.

In star-delta connected transformers, a third harmonic component flows in the delta windings, which is the exact equivalent of the missing third harmonic component of the exciting currents in the star connected primary. If the primary line to line e.m.f. is not a sine wave, it may contain any odd harmonic but the third and its multiples, provided that all three waves of e.m.f. from line to line are similar in form. Each of the harmonics in the three phases are in proper three-phase relation and will also appear in the neutral to line e.m.f. across the transformers. But where the effect of these harmonics may have been to peak the wave form from line to line, their effect will be to flatten the wave form across the transformers, that is, from neutral to line, the converse of this also being true. We should therefore expect to find that with star-delta connected single-phase transformers, a peaked e.m.f. wave form from line to line would result in a higher iron loss in the transformers than that obtained with a corresponding single-phase sine wave measurement. And similarly, if the line to line e.m.f. wave form is flattened, the observed iron loss should be less. Perhaps this may be the explanation of the difference in iron loss observed by Mr. Frank, when measured single-phase and three-phase with neutral disconnected and delta closed.

In sheet No. 10 of Mr. Frank's paper, we have a triple harmonic 0.63 amperes occurring in the secondary delta connection. Multiplying this by the ratio of transformation, we have for the corresponding primary single-phase, third-harmonic component, 3.15 amperes, and the equivalent single-phase exciting current is, therefore, $\sqrt{5.81^2+3.15^2} = 6.6$ amperes. This is 10 per cent higher than the value found for single-phase, namely 6.05 amperes. The cause of this apparent discrepancy is probably due to the wave form of the line to line e.m.f., which may be somewhat peaked, thereby resulting in a flattened e.m.f. wave form from transformer neutral to line, and therefore a higher exciting current and iron loss.

The third harmonic is not present in the line to line e.m.f. of symmetrically wound three-phase generators, but it occurs in the e.m.f. of two-phase generators and, therefore, it will appear also in three-phase e.m.fs. obtained by transformation from two-phase. The wave forms of line to line e.m.f. in such cases are not similar. Such a system may be considered as made up of a symmetrical system on which is superimposed a third harmonic three-phase system. If such a system is connected with a true three-phase system, this three-phase third harmonic component may be the cause of grave trouble.

In conclusion, the writer would like to see more data as to the effect of different polyphase connections on the iron loss of the transformers, to supplement Mr. Frank's valuable contributions.

C. A. Adams (by letter): The immense amount of data gathered by Mr. Frank on this important and interesting subject, is almost staggering, and it is quite impossible to do justice to it in a limited discussion. A somewhat careful reading developed the necessity for some additional explanations and amplifications which are here presented with the hope that they may help others similarly interested.

The area of the loop L_c, of Fig. 9, respresents the eddy current loss as well as the hysteresis loss and the loop is broader abeam than the true hysteresis loop. The eddy current energy is supplied by a current component in phase with and of the same shape as the impressed e.m.f., and the real hysteretic energy current is equal to F_E less this eddy current component, with which it is in phase.

The relative values of the maximum inductions of the various harmonics are not the same as the relative values of the corresponding e.m.fs. since the induction is the integral of the e.m.f. and therefore involves its frequency as well as its amplitude; *e.g.*, if the third harmonic e.m.f. is 52 per cent of the fundamental e.m.f., the third harmonic flux is only 17⅓ per cent of the fundamental flux.

For the purpose of explaining several points in connection with the oscillograms, it will be desirable to review briefly the various transformer connections.

In every case it is assumed that the impressed e.m.f. is balanced, symmetrical, sinusoidal and 3 phase; also that a third and a fifth harmonic exciting current are necessary for a sinusoidal flux.

THREE SEPARATE TRANSFORMERS, PRIMARIES STAR, SECONDARIES DELTA

1. *Isolated Neutral—Open Secondary Delta.*

The third harmonic exciting current cannot be supplied, therefore, The flux must contain a third harmonic, such that it would require for its m.m.f. a third harmonic current equal and opposite to the third harmonic current that would be required by the otherwise sinusoidal flux.

The star e.m.f. will then contain a corresponding third harmonic and the voltage across the open neutral will be three times the third harmonic phase e.m.f., since the three are all in phase.

The fifth harmonic exciting current will appear in the primary since the three fifth harmonic currents neutralize each other just as do the fundamentals.

The three third harmonic e.m.fs. in the secondaries will add together and appear across the open delta, thus the open delta voltage should differ from the open neutral voltage only by the ratio of transformation.

2. *Isolated Neutral—Closed Secondary Delta.*

As soon as the delta is closed the third harmonic e.m.f. in the delta will produce a third harmonic current which will supply the previously missing third harmonic exciting current and restore the flux to the sinusoidal form; but this flux cannot be quite sinusoidal since there must be a small third harmonic e.m.f. in the secondary to produce the third harmonic exciting current.

The phase e.m.fs. are therefore sinusoidal barring this very slight third harmonic, and the voltage across the neutral is practically zero.

The fifth harmonic exciting current will appear in the primary as in (1).

3. *Connected Neutral—Closed Delta.*

If the slight third harmonic in the phase e.m.fs. were to retain the same value as in (2) there would now result third harmonic currents in the primaries of approximately the same m.m.fs. as those of the third harmonic current in the secondary delta; but this would reverse the third harmonic flux and is obviously impossible. *I.e.*, the total third harmonic exciting current in primary and secondary cannot appreciably exceed its previous value in (2). Therefore, since the third harmonic e.m.f's in primary and secondary are equal, as well as the local impedances of the circuits in which the e.m.fs. act the third harmonic current will be divided evenly between primary and secondary, thus requiring only one half of the third harmonic flux and phase e.m.f. of (2).

However, if there be ever so small a third harmonic in the impressed phase e.m.f., it may (if in the proper phase) *just* supply the impedance drop of the necessary third harmonic exciting current, and entirely eliminate any need of even the slightest third harmonic flux and secondary phase e.m.f.

Then no third harmonic exciting current would appear in the secondary delta, as it would all appear in the primary.

If however the slight third harmonic in the impressed primary phase e.m.f. be of the opposite phase, it will drive the exciting current to the secondary delta by causing an increased third harmonic flux and secondary phase e.m.f.

This last is the reason why in some of the oscillograms (taken with connected neutral and closed delta) the third harmonic exciting current appears in the secondary delta, and sometimes in the primary and neutral, and sometimes in both.

Curves 69 and 70, sheet 11, analyzed in Figs. 24 and 25, show a small third harmonic exciting current in the primary lines and neutral, but as the third is less than the fifth it is reasonably certain that the larger part of the third is to be found in the closed delta, although no oscillogram thereof is given. The fundamental, fifth, seventh, and eleventh harmonics in curve 70, Fig. 25, are due to an unsymmetrical system, as they would otherwise cancel out.

The curves of sheet 2 also show the harmonic exciting current divided between the primary and secondary for the same case of connected neutral and closed delta, the larger part being in the primary, while for the case of sheet 11 the larger part was in the secondary.

4. *Connected Neutral—Open Secondary Delta.*

In this case each transformer is entirely independent and the exciting current will flow in the primary as in the case of a single transformer with sinusoidal impressed e.m.f. and open secondary.

The three third harmonic exciting currents will add together in phase in the neutral while the fundamentals and fifth harmonics cancel out.

If the impressed e.m.f. on each transformer is absolutely sinusoidal, the induced e.m.f. and flux will be distorted an imperceptible amount by the internal impedance drop due to the third and fifth harmonic currents, and there would be a very slight third harmonic e.m.f. across the open delta, the fifth cancelling out with the fundamental. These are, however, too small to be of any practical importance.

The considerable third harmonic e.m.f. across the open delta in curve 15, sheet 3, must be due to a third harmonic in the impressed e.m.f.; a careful inspection of curve 12 will show this to be the case.

Curve 75 of sheet 12 also shows a third harmonic e.m.f. in the secondary for this same connection, but in this case it is only ½ per cent whereas in curve 15 it is 5 per cent. In this case (curve 75) it may therefore be partly if not largely due to the e.m.f. distortion produced by the large third harmonic current in the primary.

One Three Phase Transformer

If the three cores are *absolutely symmetrical* and the impressed e.m.fs. balanced, there can be no third harmonic flux in the main magnetic circuit. Any such flux in the core legs must return *via* the surrounding non-magnetic material; *i.e.*, the reluctance of the third harmonic flux path is many times that of the fundamental flux path.

1. *Isolated Neutral—Open Delta.*

In this case there can be no third harmonic exciting current, therefore there must be a third harmonic flux of sufficient magnitude to eliminate the need of a third harmonic exciting current; *i.e.*, a flux which would require for its m.m.f. a current equal and opposite to the third harmonic current that would otherwise be present. But the reluctance of the third harmonic flux path is so large (as explained above) that a negligibly small third harmonic flux is sufficient to neutralize the third harmonic current. Thus it is that the leg e.m.f. is practically sinusoidal and the voltages across the open neutral and open delta are zero, in spite of the fact that there is no third harmonic exciting current, see Sheet 21.

It is obvious that closing the neutral or the delta or both would have no appreciable effect upon the curves, as is shown on sheets 18, 19 and 20.

In a similar manner numerous other interesting points can be explained.

J. J. Frank: The paper was prepared primarily for the benefit of operating engineers to emphasize the great practical value of an investigation of the distortion of current and potential wave shapes found in the common banking of transformers. The absence of any discussion by operating engineers is somewhat of a disappointment.

The confirmation by Silvanus P. Thompson of my conclusion that the current wave distortion depends only on the variations in the permeability of the steel is very gratifying.

The discussion by C. A. Adams, calling attention to the possible amplification of the data submitted in my paper, is also very gratifying.

A paper presented at the 248th meeting of the American Institute of Electrical Engineers, San Francisco, May 6, 1910.

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TRANSMISSION LINE CROSSINGS OF RAILROAD RIGHTS-OF-WAY

BY ALLEN H. BABCOCK

It is necessary to protect:

1. The railroad communication circuits (telegraph, telephone and signal) from mechanical injury and from contact with high tension wires.

2. The train crews from personal injuries due to sagging or fallen wires.

3. The trains themselves from mechanical damage and from the liability of fire should a wreck occur at the crossing point.

4. The railroad structures from damage by fire due either to crosses between communication circuits and fallen or sagging transmission circuits, or to high potential electromotive forces induced therein by excessive unbalancing of the transmission circuits.

Having in mind the fact that contact with transmission circuits is dangerous to both life and property, it was natural that the early attempts at protection were of the nature of guard wires, in some form or other.

Many of us have had experience with some such device. Nearly all of us who have had sufficient experience have found unsatisfactory all forms of guards as yet devised. Even those of the deep basket type have failed at times to give complete protection. Furthermore, any pole line is worked at about minimum factor of safety; hence, to increase the load on it at the very point where maximum security is demanded is an engineering anomaly. Prophecy after the fact is easy.

The next step is obvious; to construct the transmission line with maximum factor of safety both in the crossing span and also in each of the adjacent spans, so that nothing short of a general catastrophe shall bring the line into dangerous proximity to the railroad right of way. So well recognized is this principle that the power and the railroad interests are now working in harmonious conjunction to devise an economical mechanical and electrical construction for these crossing spans, so much more secure than that of the transmission line elsewhere, that if ever failure occurs it must be at some other point.

In general, it is advisable, wherever possible, to place underground all low potential power circuits, and communication circuits. The following general specifications cover the points that are now under discussion between the power and railroad companies.

GENERAL SPECIFICATIONS FOR THE CONSTRUCTION OF OVERHEAD ELECTRIC LIGHT OR POWER LINE CROSSINGS—

GENERAL

1. All crossings carrying current at more than nominal 2,300 volts to ground shall come under the provisions of these specifications, unless special conditions in large cities or otherwise shall make a modification thereof necessary or desirable.

2. Complete drawings shall be furnished in duplicate for approval before construction is commenced.

3. The power company shall give the railroad company one week's notice prior to the commencement of work.

4. All work, including the materials entering into the work, shall be subject to the inspection and approval of the railroad company.

5. The power company shall protect the railroad company against any suits for damages arising by reason of any patented devices being used in the work under these specifications.

CLEARANCES

6. Vertical clearance, under the most favorable conditions of temperature or sag, shall be as specified by the railroad company, but shall not be less than 35 ft. above the top of rail and not less than 10 ft. above any existing wires on the right of way.

7. Side clearance for structures that it may be necessary to locate on the railroad company's right of way shall not be less than 10 feet from the center of the nearest present or proposed track.

CROSSING SPAN

8. The crossing span shall be carried on towers or poles which shall be self-supporting under the most unfavorable conditions of loading, or of broken conductors.

9. Supports for the crossing span, and for the adjacent spans on each side, are to be generally in a straight line and preferably at right angles to the railroad.

10. Conductor supports shall be guyed away from the tracks in such manner as to make it impossible for the supporting structures to fall toward them.

11. In general, steel towers shall be used, although under certain conditions wooden structures, with concrete or other approved foundations, may be permitted.

12. Foundations shall be designed to resist double the greatest tendency to overturn under the most unfavorable conditions, due to breakage in the line or otherwise.

13. In designing tower foundations, the weight of earth shall be taken at 90 lb. per cu. ft. and the weight of concrete at 140 lb. per cu. ft.

14. When towers are used, they shall be constructed of soft or medium soft steel, thoroughly painted or galvanized.

15. Tower construction shall be shown or specified in detail on plans submitted for approval by the railroad company. They shall give sufficient data so that stress diagrams may be constructed for the given loads.

16. All steel structures on the railroad company's right-of-way shall be grounded in an approved manner and shall be provided with approved danger signs.

17. Steel structures supporting the crossing span shall have a factor of safety of not less than three, based on the ultimate strength of the material and considered under the most unfavorable conditions of loading, wind and broken conductors.

18. Wooden structures supporting the crossing span, and also wooden crossarms, shall have a factor of safety of not less than five, based upon the ultimate strength of the material and considered under the most unfavorable conditions of loading, wind and broken conductors.

All the following sections shall apply to the crossing span and to each span adjacent thereto:

PINS

19. Material: cast steel, iron pipe, malleable iron or other crude metal, galvanized.

20. Where wooden crossarms are used, a grounded metal strip must connect all pins electrically.

21. Pins shall be designed for factor of safety of three, under most unfavorable conditions.

INSULATORS

22. Material: porcelain only above 7,000 volts, and porcelain or glass below 7,000 volts.

23. Insulators shall be designed for voltages 25 per cent in excess of the rated working voltage of the other insulators on the line.

24. Pin type insulators shall have metal bridge caps, or the equivalent.

25. If suspended type of insulator is used, all connections between the parts of the insulator shall be of the interconnected link type, or its equivalent. Whatever type of insulator and attachment is used, the conductor must hold to the supporting structure even if the insulator is mechanically or electrically shattered.

26. Clearance: Insulators shall clear all parts of the supporting structure (except pins and crossarms), not less than 12 in. up to 24,000 volts, plus one inch per 10,000 volts additional.

CONDUCTORS

27. Material: copper, aluminum or other non-corrosive metal. For spans carrying current up to 5,000 volts, minimum size No. 6 B. & S. copper, or aluminum, or other material or alloy of equivalent strength. Above 5,000 volts, minimum size No. 0 B. & S. copper, not less than seven strands (or six strands around a non-conducting center), or aluminum, or other metal or alloy of equivalent strength.

28. Tension shall be adjusted to be equal on each side of the supports of the crossing span.

29. Clearance between conductors and tower structure (except pins and crossarms) shall be not less than 12 in. up to 24,000 volts, plus one-half inch for each additional 1,000 volts.

30. Minimum clearance between conductors shall be not less than 24 in. up to 24,000 volts, plus one inch per 1,000 volts additional.

31. The conductors shall be clamped mechanically to the insulator.

32. The conductors shall be connected to the supporting structure at an auxiliary connection that will insure positive grounding of the conductor in case of failure of the primary insulation.

33. All crossing conductors shall be wrapped or shielded against arcing where they pass over the insulators or through clamps.

34. No splicing will be allowed in any of the three spans named.

35. Crossings shall be designed for one-quarter inch ice radially of weight 60 lb. per cu. ft., plus the weight of the conctduor, plus a horizontal wind pressure of 20 lb. per sq. ft. on a projected area of the ice covered cable. (Obviously where ice is never formed, that element of the calculation can be omitted.)

36. Maximum of allowable stress shall be not more than three-tenths of ultimate strength.

37. All calculations shall be based upon a temperature range of 130 deg. fahr.

The foregoing specifications are tentative in the sense that while they represent the present mutual understanding of the interested parties, they have been adopted merely as a provisional basis for discussion. As such they are submitted for the consideration of the members. It is hoped that your criticism will be construction as well as destructive.

The following table will serve to show that the subject is one not to be disposed of lightly. With 482 crossings to be legislated for on a single trunk line, it is easy to see that the agreement reached must be reasonable and equitable, or it will not stand.

CLASSIFICATION OF POWER CROSSINGS. SOUTHERN PACIFIC COMPANY

Division	Under 2500 volts	2500 to 5000 volts	5000 to 10000 volts	10000 to 15000 volts	15000 to 25000 volts	25000 to 35000 volts	35000 to 65000 volts	Over 65000	Not listed	Total
Coast..........	119	3	30	13	8	0	5	0	1	179
Western........	47	3	9	7	3	3	42	3	3	120
Sacramento.....	42	6	6	0	14	0	12	5	—	85
Shasta..........	11	0	0	0	8	0	3	0	5	27
S. Joaquin......	6	0	0	3	2	18	0	5	2	36
L. Angeles......	1	0	0	0	18	6	0	0	2	27
Tucson.........	1	0	0	0	0	0	0	0	0	1
Salt Lake.......	1	0	1	2	0	0	2	0	1	7
Total..........	228	12	46	25	53	27	64	13	14	482

DISCUSSION ON "TRANSMISSION LINE CROSSINGS OF RAILROAD RIGHTS-OF-WAY" SAN FRANCISCO, CAL., MAY 6, 1910.

John Harisberger: I would ask Mr. Babcock if he has any suggestions for a satisfactory crossing for the right of way by transmission lines?

A. H. Babcock: The only suggestions are those embodied in these specifications. The first and second paragraphs cover the point, that up to the present no basket or guard, or similar construction has been found satisfactory. The power companies themselves have attempted to develop that sort of thing and have found that after it was put in service there were so many disadvantages, that the device had ultimately to be abandoned. It is thought now that the only satisfactory way of handling the subject is to make the crossing so strong mechanically and electrically that it cannot come down at that point.

John Harisberger: The requirements of the Northern Pacific have been to place poles on either side of the track so high that even if a wire broke it would not reach at most the top of a box car. It seems to me that that would be the requirement if the right of way were not of such width that it would be impractical.

A. M. Hunt: In paragraph 27, "Conductors," Mr. Babcock has stated that "material: copper, aluminum, or other non-corrosive metal," should be used. It would appear to me that the element of strength in the conductor over the track is the main essential, and that perhaps could be better attained by the use of heavy galvanized steel conductors, such as cross the Straits of Carquinez, used by the Bay Counties Power Company. They are steel cables and are always kept painted and in first class condition. The possibility of rupture is very much less than if they were of copper or aluminum, or material of equal conductivity. That one point of exception can well be taken to the specifications.

C. F. Adams: In clause No. 19; "Material: cast steel, malleable iron, or other crude metal, galvanized." Under that specification a cast iron pin could be used. In paragraph 23 it states: "Insulators shall be designed for voltages 25 per cent in excess of the rated working voltage of the other insulators on the line." I believe that if a step of that kind were taken, it would result simply in the taking of a succession of steps. In other words, the general public would call for as good an insulation as the railroad company did, and then the railroad company could call for 25 per cent in excess of what the public were then getting. It seems to me that what is proper for the entire system should be sufficient for the railroad company.

There is one other point that I note here, which does not seem to have been embodied in the presentation of this paper. It states: "In general, it is advisable wherever possible to place underground all low potential power circuits, and communication circuits." I believe that clause is correct, and I think also that it should be applied to communication circuits of telephone signal and telegraph lines by the railroad companies. I know of nothing better than a few feet of earth and a little lead to protect from a high-tension circuit falling to the ground.

Lewis B. Stillwell: I agree fully with Mr. Babcock that special and adequate protection should be provided in all cases where high-potential transmission circuits cross railway lines. I do not think, however, that the problem is one of any great difficulty. It is to be noted that the accidents mentioned by Mr. Babcock, with one exception, were not occasioned by reason of the fact that the circuits were not properly protected. They were purely mechanical accidents and due to gross carelessness. In Italy, notably on the Valtellina, a wire net is suspended beneath the transmission circuits where highways are crossed. These are somewhat awkward in appearance, but properly erected and maintained, they appear to afford adequate protection. Crossings of this character should be built upon the same principles upon which bridges are constructed, that is to say, they should be built so that the line will not fall down. As a bridge problem, railroad crossing by a transmission circuit is very simple. Ample factors of safety are practicable and a little care will provide against failure. If a circuit breaks between two poles or towers on opposite sides of a railway crossing, provision should be made for grounding that circuit before it can touch the locomotive or car passing beneath it. This can be accomplished by placing a grounded conductor in a horizontal position, where the falling conductor must touch it before reaching the top of the car.

As regards the specifications suggested by Mr. Babcock relative to conductors, it would seem that while this is unobjectionable in general from the standpoint of the power company and should be satisfactory to the railway company, specification No. 27 could be made more definite by requiring in general terms a mechanical factor of safety rather than prescribing arbitrarily the size of the wire with reference to the voltage. It would be reasonable to require that the span crossing the track be constructed with a very high factor of safety. In conjunction with this, some plan of grounding the circuit and cutting it out automatically in case the wire breaks, would be unobjectionable.

I understand that in the judgment of the engineers of the Pacific Gas & Electric Co., automatic circuit breakers are not yet developed to a point where they can be relied upon for very high potentials. This being the case, if the two towers supporting the wires which span the railroad be connected electrically by adequate earthing or by conductors and provision made for effectively grounding the conductor in case it breaks, I do not see how any material damage to a car is liable to occur.

P. M. Downing: There are a few points in the paper which I think might be improved upon slightly, but in general, I think the specifications as proposed, come nearer meeting the approval of the power companies than anything that has yet been submitted. Our experience here on the Coast in the matter of protective devices where power lines cross railroad rights of way, is a rather long one. We started in with the idea of using some sort of a basket device to catch the wires in case they should break at these crossings. These basket devices consisted of wires carrying a sort of lattice work in order to catch the broken circuits, but we found that these baskets were more of a menace than protection, for the reason that they were very hard to maintain on a long span, and where the railroad right of way was wide, the strains thrown on the supporting structure was very great, and we had so much trouble with those that they were finally abandoned.

The specifications, as I understand them after going over them very hurriedly, provide for good mechanical construction. To my mind, this comes nearer meeting all requirements than anything else which could be submitted. However, as I say, there are a few points which, to my mind, might be improved upon, but I have not gone into the specifications fully enough as yet to be entirely familiar with them.

Markham Cheever: To one who has been interested in this subject for a considerable time, the prefatory remarks in the paper appear as a most excellent statement of the present status of the problem. The old basket type construction as pointed out by the author is obviously inadequate and introduces an element of hazard greater than the danger it prevents. Numerous other designs have been proposed, many of them involving a tension in the crossing span less than the tensions either side, and this again introduces additional risk by reason of the many dead-end connections. It is now being widely recognized that a more reliable construction is produced by running each line conductor straight through, avoiding any splices or dead-end connections in the crossing or adjacent spans, and maintaining uniform tensions. A design based upon this principle has been largely used for the crossings of high tension lines over the tracks of the New York Central Railroad. Two towers are placed close to the railroad right of way, one on either side. The precautionary feature consists of auxiliary ties to each line conductor from insulators supported on the track sides of the structures and at lower elevations than the main insulators. Should the conductor break on the supports adjacent to the track or at any point behind, allowing the conductor to slacken, the auxiliary ties hold the crossing span suspended, at the same time efficiently grounding it.

Sidney Sprout: Some gentleman made the remark a few moments ago that a few feet of earth between the transmission line and the telegraph line was probably the safest insulator that could be had. I have noticed that the telephone company, the Pacific States, at its crossing with street railways is making a general practice of putting a cable underneath the streets. I will offer just a few suggestions, as I have not read the specifications through since I came in. I did not expect to take any part in the discussion, but I think if we would reverse the specifications somewhat, where there is a trolley crossing or a high tension transmission crossing of the railroad, considerable difficulty or danger can be eliminated by the railroad companies putting every 200 feet their telegraph and signal lines underneath the ground in a cable. I believe they do that at present at a number of places along the lines where they enter the depots. This seems to me to be a way to avoid the difficulty that came up in one of the cases mentioned at Antioch, where the towers were built carelessly, or otherwise, and dropped across the line, and that would make, of course, considerable confusion. I think that the transmission companies or the power companies would be perfectly willing to pay for any expense of running underground at such places as they cross. Of course, the other dangers of lines coming down on the track, and the trouble, the mechanical trouble, of engineers, and so forth, would not be avoided by this; but it seems to me that the greater part of the danger of which Mr. Babcock speaks, would be avoided by a very slight expense of running the wires underground. I think that the transmission people have racked their brains and spent considerable money for suitable means of crossing railroad lines, as well as telephone and telegraph lines, by which they might be saved from annoyance or the liability of danger that they are causing by running overhead. As some gentleman has said here, the very means that they expected the most of, seemed to fail; and I believe that if we look on the other side of it, that the telephone people have done it probably unintentionally, or possibly because electric people have delayed in putting in proper protection—and of course they have protected themselves—but it seems to me that they have solved one of the great troubles and annoyances by putting all of their lines underneath the track where they cross street railways or steam railroad lines. I know they still call on transmission people to protect their lines, but I believe they would rather put their lines underground than to run the risk and danger of the wires breaking and coming down on to a trunk line service. A great many of our lines cross the telephone and telegraph lines between the main stations, Los Angeles, San Francisco, and Portland, and it means considerable to them if it does break down. I appreciate the necessity of something being done, and I think that Mr. Babcock's paper is one that we should consider very seriously, and I think that the Institute should take some steps regarding the matter, instead of letting it drop without more serious thought than what has been already brought out.

J. P. Jollyman: Mr. President, I believe that it is possible for the power companies and the railroad companies to reduce their troubles to a minimum. It is undoubtedly possible to construct a protection that would be absolute, but the question of cost would be prohibitive, except in very special cases. The power companies are interested in the matter nearly as much as the railroad companies, and anything that will be to the advantage of the one, would be of advantage to the other. The matter of underground crossings is something that would have to be studied very carefully, for an underground crossing in connection with a telephone, telegraph or signal service line may add to the difficulty, of satisfactory operation. In some cases the companies operating these lines might even prefer to go overhead and take their chances. I think, on the whole, that the specifications as read by Mr. Babcock, if faithfully carried out would lead to as safe a crossing as can be reasonably expected under present conditions.

R. W. Van Norden: I have not read this paper as carefully as I would like, but, from the discussion which has been given so far, I cannot see but that the necessary points are covered as well as they can be, as Mr. Jollyman says, without too much cost. On the section that Mr. Babcock spoke of, on the Southern Pacific, we have built a good many crossings, and while we have used small wire, I do not remember that we have had an accident where it affected a telegraph system, but possibly once, and that was not at a crossing, but was in the case of a blast at Rocklin that threw the transmission line down, and the blast affected the telegraph signal system. I do not recollect that there has ever been any serious break at any crossing. The only system we used was the basket system, which I do not particularly believe in. There have been some experiments made along the lines suggested, of grounding, so that in breaking it grounds before striking earth. Those have not been carried out very carefully, so I cannot tell you what the experiments resulted in.

President Stillwell: I do not fully agree with Mr. Cheever in regard to the basket suspension plan. Its effectiveness is purely a matter of construction and maintenance. In Italy, apparently they maintain it properly—that is what we do not always do very well in this country. We put up devices of this character and then fail to maintain them. In my opinion, the basket construction, while not the best, can be made effective in the case of comparatively short spans, if properly maintained.

R. W. Van Norden: There is another point that I think of. Mr. Hunt spoke of putting up steel in place of copper or aluminum. I know of one case where we used steel in spans, and one of them was across a railroad track. Some of the wire was copper, very small No. 6, I think, the span was between 800 and 1000 feet long. We used also No. 6 steel telephone wire. The telephone wire broke in the winter a number of times, apparently due to snow loads on the line, but the copper wire would not break at the same time. The steel would pull out; it would not make a quick break, it would pull out to about one-half of its diameter, and then it would break, but the copper would not break at all.

C. F. Adams: I would like to reply to the suggestion of the President concerning the matter of grounding. That would be operative on lines of limited length and low frequency. On lines approximating the length that you will find here in California, with a frequency of 60 cycles, if it is grounded 100 miles from the station, it does not give you enough short circuit current at the station to overload the generator and carry it beyond normal. That has been tried out, and it has been thoroughly demonstrated that a short circuit may occur on any one of the three phases and yet the operating station may not have sufficient indication of a short circuit to really warrant them in pulling their current off the line.

President Stillwell: This sort of a paper is an admirab'e one in my opinion; it is not overloaded with unnecessary explanations; it is precise and explicit, and is a very essential start toward standardizing a very important matter, and I think that at the proper time, the standardizing committee of the Institute operating, for example, in conjunction with the proper committee representing the railways, might agree once and for all upon specifications which would be adhered to. That would save a great deal of trouble to all concerned, and I see no reason why a question of that kind cannot be taken up in that manner.

A. H. Babcock: Mr. Harrisberger suggests that adequate protection can be secured by using high poles set so close to the right of way that a broken wire will not be able to strike the tracks. Doubtless he has in mind narrow rights of way. The Western Railroads often have 400 foot rights of way so that it is difficult to see how poles can be erected high enough to prevent a broken wire striking the signal and telegraph circuits.

As a rule the wires break near the support, either by vibration or by burning.

Mr. Hunt mentions the possible use of iron wire or steel wire under section 27 of specifications, and cites the case of the Carquinez Straits span where the cable has been operating for a great many years with great success. I think he overlooks the point that the Carquinez cable is so heavy that a man can be sent out on the cable to inspect it and to maintain it. In certain sections of this country the salt fog will eat up an iron wire in a very short time. Experiments made along the east side of San Francisco bay show that the ordinary galvanizing of overhead trolley line parts is by no means an adequate protection, and that the metal rusts very quickly. For these reasons it is doubtful that any small iron wire, say No. 4 or

No. 6, can be used to make a thoroughly safe construction, without a great deal of maintenance cost in the way of replacements. Usually a transmission line wire is put up and forgotten as long as possible, so that the railroad company has reason to be suspicious of iron wire crossings.

If I understand Mr. Adams correctly he feels that the iron pipe pin would be barred out by section 19. Possibly it might be well to make an amendment there and mention specifically iron pipe.

The President has referred to the protection used on one of the Italian lines with which I am not familiar. Some of the French lines use a through span bridge over the tracks, through which both the telephone and transmission wires are carried. It is difficult to imagine a more complete protection than is afforded by such construction, but it is very expensive. It is neither equitable nor possible to attempt to shift the total burden of the expense of such crossings entirely from one party to the other. It is properly a matter of joint responsibility and interest. The broad principle involved in this matter is met by the railroad man every day in the crossings of his rights of way with other railroad rights of way. The senior road at the crossing does not stand much of the cost, while the junior road bears the greater part of it. A road that is senior in one place may be the junior road in some other locality because lines are being extended all over the country. We have a number of such cases—for instance, in connection with the power transmission lines now operating in this part of the country. In these cases undoubtedly the railroad company will be obliged to stand the greater part of the expense.

The foregoing remarks will refer also to Mr. Sprout's and Mr. Jollyman's discussions.

The suggestions made by the president that the railroad companies and the Institute shall join in a general discussion of this subject seems to me to be one that may have a very far-reaching consequence. I, for one, would be very glad to see such an arrangement brought about.

Ralph D. Mershon (by letter) Mr. Babcock's paper deals with a subject to which I have given considerable attention. Some time ago I wrote an article dealing with the subject.* It embodied my ideas as finally crystallized after various discussions and investigations relating to the subject. The endeavor was made to lay down the conditions which should be met in transmission line crossings in order to ensure safety. I quote these conditions, from the article, as follows:

(*a*) It should be so constructed that the line conductors (line wires or cables) and the supporting structures at each side of the track would be of proper strength to withstand the

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*" Transmission Line Crossings over Railroads", *Railroad Gazette*, February 7, 1908.

ice and wind loads which might come upon them. It should be self-sustaining; that is, should be capable of standing up under the action of wind and ice without reference to the remainder of the line, so that the line on one or both sides of the crossing, might break without interfering with the crossing itself.

(*b*) There should be sufficient overhead clearance between the line and the track, so that there would be no possibility of contact except by deliberate intent.

(*c*) The line conductors should be far enough apart so that they could not swing together.

(*d*) The line conductors should be sufficiently massive so that an arc might exist between them for several seconds, without danger of burning or melting them off.

(*e*) If the supporting structures are of steel, or the insulator pins are of metal and the pins connected to each other, or to ground, the insulators should have cast metal caps cemented upon them. These caps, or extensions of them, should extend out on each side of the insulator for some distance along and underneath the conductor, in order to further protect the conductor, or else the conductors should have, in addition to the caps, a protection from arcs in the form of a serving of wire upon them for some distance on each side of the insulator. The result of such protection will be that an arc formed near the insulator will expend itself upon the serving wire, or metal casting, instead of upon the conductor itself.

Mr. Babcock has gone into this matter in greater detail than was attempted in the article above referred to. In general, his specifications appear to me to conform with the ideas as laid down therein, though they do not seem to me as clear as they might be in regard to the matter covered by the latter part of (*a*). Apparently his specifications are intended to cover the construction of the supports and cables not only of the crossing span but of the adjacent spans on each side of the crossing span, and they contemplate the construction of these three spans of equal strength. Yet in item 17 he specifies the strength of the steel structures for the crossing span only, and says nothing about the supports for the two adjacent spans. It seems to me that, in general, it were better to so design the three spans that those adjacent to the crossing span could go down without injuring the crossing span. I will deal with this matter further in my remarks under ¶ 27.

There are a number of additional minor points in Mr. Babcock's specifications with which I do not quite agree. These differences will appear from what follows, in which I shall refer to such of the items of the paper as seem to me should be modified, designating them by the figures used in the paper.

¶6. This item contemplates that the power wires shall necessarily pass *over* the wires already on the right-of-way. It seems to me that there might often be cases where it would be safer and better to have the power wires pass *under* the existing wires, the latter crossing the power wires with a span so short on structures so high that, even though the existing wires should break near one structure, they could not reach the power wires.

¶20. It seems to me that not only should the pins be electrically connected to each other, but that this connection should be effectively grounded, especially if the wooden cross-arm is carried by a wooden structure. In the case of a metal cross-arm carried by a wooden structure, the metal crossarm should be grounded.

¶25. In the present state of the art of making the inter-connective link type of insulator, it may be working a considerable hardship upon the power transmission companies to require their use. And, so far as my experience goes, the cemented form of suspension insulator can be safely depended upon.

¶26. I am not quite sure that I understand this item, but if I do it seems to me the clearance provided is rather small. For 100,000 volts, for instance, it would be only 19.6 in.

¶27. I do not quite see the reason for making the minimum size of conductor less with lower voltages than with higher ones. Other things being equal, the danger of burning a conductor is greater with a lower voltage than with a higher one. Because with the same power capacity in each case the arc with the lower voltage would be heavier than with the higher. Inasmuch as the power capacity of the circuit as well as the voltage has to do with the amount of damage that might be done by an arc, it would seem to me better to either specify the size of the conductor with reference to both the power and voltage, or else to specify for all cases a conductor so heavy as to take care of any condition which might be met with in ordinary practice. It seems evident from this item and the next one that Mr. Babcock contemplates that the same size of conductor shall be used upon the crossing span, and the two spans on each side thereof. I should suggest the consideration of a great deal smaller and weaker conductor on each of the adjacent spans, so that if the transmission line itself should go down the conductors of these spans might break before injuring the crossing span.

¶32. I am not sure what this paragraph means. If it refers to the use of the device consisting of an auxiliary insulator and a connection from it to the line cable, together with a grounded guard against which the line cable is supposed to land in case it is burned off, the advisability of such provision seems to me questionable. I should prefer to make the cables heavy enough, and so protect them near the insulators, that they would be capable of successfully withstanding a power arc until the circuit breakers controlling the power line opened, or until the arc ruptured itself, in case the circuit breakers failed.

¶35. I do not see why the horizontal wind pressure should be added to the weight of the conductor and its covering of ice, instead of taking the resultant of the weight and wind pressure. I presume, that this wording of this item is an inadvertence.

Frank F. Fowle (by letter): The paper by Mr. Babcock agrees very well in its general recommendations with the conclusions presented by the writer two years ago in a paper prepared for the Association of Railway Telegraph Superintendents, and since published. The writer also attacked the fallacy of screen and basketwork protection some four years ago, which Mr. Babcock aptly characterizes as an engineering anomaly.

In general the problem presented is that of designing a transmission line crossing so that it shall be stronger electrically and mechanically than the balance of the line, and so that the probability of failure shall be practically extinguished. The crossing should compare with the balance of the line as follows:

1. The mechanical and electrical factors of safety should be greater.
2. The conductors should have greater conductivity per unit of length.
3. The conductor separations should be greater.
4. The entire structure should be absolutely fire proof for voltages above 10,000.
5. The protection against arcing should be greater, and against the effects of arcing.

A factor of safety in mechanical stresses of 3 is often recommended for dead loads, but in view of the possibly great damage that would result from failure, a factor of 4 seems to me no more than adequate. In choosing a factor of safety, the elastic limit as well as the ultimate strength should be considered.

For voltages below 10,000 where steel structures are for any reason not possible, the cross-arms and pins should be of steel in any case. Single wooden poles are not desirable, and some form of fixture made of two or more poles, such as an "*A*" fixture, or an "*H*" fixture, seems very essential. Wooden poles should be fire-proofed for several feet above the ground, and the butts should be creosoted. A factor of safety of 6 is recommended for all timber. Steel cross-arms and pins on timber structures should be thoroughly grounded.

Insulators designed for electrical stresses 25 per cent in excess of the main line would seem to be no more than adequate, especially in view of the fact that the damage done by lightning, and the maximum stresses caused by it, are largely local. A larger margin of safety in the insulators appears to be desirable in districts where lightning is severe.

As regards conductors, the unreliability of single aluminum strands of small size prevents their use; and aluminum should always be stranded. No. 6 B. & S. copper has an ultimate strength of nearly 1,300 lb., and is hardly suitable for crossings of this character. A minimum size of No. 2 B. & S. or No. 0 B. & S., stranded, will be better practice. If this size of copper has more than the necessary conductivity, copper-clad steel of corresponding strength may be substituted. The conductivity and diameter of conductor at the crossing should exceed that in the main line by at least 25 per cent.

Low-tension circuits carried on the high-tension line should be treated at the crossing as though they were high-tension circuits, for a failure on the line at some distance from the crossing may impress a very high tension on these circuits for a short time, causing them to break down at numerous places. If this proves to be a more costly procedure than carrying them underground at the crossing, the latter course is the obvious one.

Sleet loads vary greatly in different parts of the country, according to climate. A radial thickness of ¼ inch may suffice in California or in the extreme South, but it is much too small in the Central and Eastern states. The writer has seen accumulations on small wires in Illinois of about 1 inch radius, in severe storms. The records of the Weather Bureau will frequently furnish the necessary data upon which to base safe practice in this respect.

A wind pressure of 20 lb. per sq. in. on flat surfaces normal to the wind, computed from the formula,

$$p = 0.004 \ V^2 \tag{1}$$

corresponds to a velocity of 70.7 miles per hour. The writer found that for a period of ten years, at Chicago, the highest recorded velocity during a severe sleet storm was 50 miles per hour. The Weather Bureau maxima are based on observations at 5-minute intervals with a cup anemometer. Observations made with the Dynes pressure anemometer show instantaneous velocities, as much as one-third in excess of the 5-minute maxima of the cup anemometer, uncorrected. This indicates instantaneous true maxima as high as 67 miles per hour.

The Chicago observatory is 310 ft. above the street level, and it is reasonable to expect that the corresponding maxima at heights of 50 to 60 feet are considerably less, but how much less it is not possible to say with great accuracy. The contour of the ground, the presence of sheltering trees and buildings, and the general topography of the surrounding country, all have a vital bearing upon the wind pressures that may be expected at any given place.

The matter of maintenance is as important as that of design or construction, in providing safety for all time. Non-corrosive conductors, such as copper and aluminum, will give no trouble unless there are certain gases present in considerable quantities, such as occur where there is a profusion of smoke from soft coal or fumes from chemical works. The corrosion of steel, however, is another matter and a serious one. Galvanizing is an initial protection, but not permanent; and it cannot be renewed. It has a life of perhaps 15 years. Painted steel structures, periodically inspected and repainted, should have a much longer life, probably three times as great for permanent structures. The initial factor of safety cannot be maintained unless corrosion is prevented. The same is true with respect to the decay of timber. Therefore it appears to be an essential part of a crossing contract between a power company and a railroad company to provide for periodical inspections, and to place a limit upon the safe dimensions of structural members, so that the processes of corrosion or decay shall not defeat the original purpose.

Another phase of this problem is a legal one, which assumes considerable importance from the railroad point of view. Crossings on private right of way are under the control of the railroad company, but this is not true as regards crossings upon highways or public roads. The latter in most cases are subject to no further regulations than the state laws impose upon all wire crossings, which commonly specify a minimum clearance and sometimes minimum spans, steel pins and double cross-arms. It becomes the duty of electrical engineers to rectify this defect and point out the dangers. Legislation is much needed to place in the hands of the state railroad commissions the necessary authority to deal with such crossings and properly safeguard them.

Percy H. Thomas (by letter): *General.* The crossing of railroad rights of way by power lines represents much the same problem as the crossing of public telephone lines, the latter perhaps offering the widest exposure of the public to danger. Therefore it would perhaps be well to consider the two cases together.

In general the plan outlined in the paper is sound. It will probably however be found, as in the past, impracticable to provide a single set of hard and fast specifications to cover all cases. Crossings vary greatly, not only in importance and exposure but as well in physical characteristics; from the crossing of a main line railroad by a minimum length span of a power line to the very long span, possibly crossing a river with a little used branch railway line along one bank. Flexibility in the specifications could be obtained presumably by the relaxing of specific requirements where there appeared occasion for such a course, and where local conditions furnish justification therefor. The mutual sense of fairness between the engineers of the power and the railroad or telephone company must be relied upon to arrive at an equitable result in each case, the general specification giving a starting point and expressing the best practice for the average condition.

As an example of varying conditions to be determined on by mutual agreement in any particular case I may mention the thickness of ice to be assumed in calculating break down strength.

While it may be well as a matter of principle to provide for the furnishing of full drawings to both parties, and serving long notice of construction with the idea that the company being crossed will check up all details of the design, experience will undoubtedly show the precaution to be omitted in a majority of cases.

Specific Points in the Specifications.—As one of the most dangerous possibilities is the burning off and dropping of a conductor, as by the puncture of an insulator, it may in some cases be well to support the span by a second auxiliary insulator which may furnish mechanical support even if the line conductor be elsewhere grounded.

In cases of wooden cross arms where the nearby spans utilize ungrounded pins it would be well to ground the pins for several poles on each side of the crossing as otherwise lightning reaching the line near the crossing might find an easier ground path at the crossings insulator which must have a grounded pin.

¶8. Guys properly installed should be considered as forming part of the strength of the structures. This applies as well to ¶12.

¶23. The requirement of a special insulator at the crossing while entirely reasonable in one sense will cause a great deal of labor in many cases and perhaps disproportionate expense. if for example a special structure for the tower were thereby required.

It is an open question whether the interlinked type of suspension insulator or the concentric type is really safer in preventing the dropping of the line in case of trouble. The weakness of the interlinked type is the ease with which the link may be burned off if the insulator is punctured.

¶26. This clearance around the insulator seems a little excessive and hardly necessary in all cases.

¶27. This section should be so worded as to clearly permit well galvanized steel.

¶28. It will not always be feasible and it will often be trivial to equalize the strain in the span conductors at the cross over.

¶32. This section is not very clear.

¶33. The serving should extend to some distance on each side of the insulator.

¶35. This maximum wind stress seems too high for cylindrical surfaces; the value 12 has often been used. Of course in special localities the higher value may be warranted.

¶36. Taken in connection with all the other allowances made for safety it would seem safe to use a higher portion of the ultimate conductor strength, especially with a stranded conductor, than 0.3. For instance, 0.4 or even more has frequently been used. In taking extreme precautions in so many features an excessive total may be reached.

Nothing is here specified about the simultaneous conditions that shall be taken to represent the most severe conductor strain.

A. H. Babcock (by letter): Mr. Mershon considers that the two spans adjacent to the crossing span should be constructed under the same specifications as the crossing span. Usually these two spans are on private rights-of-way with which the railroad company is not concerned, unless a mechanical weakness in these spans shall be the cause of a failure in the crossing span, a contingency paragraph 10 is expected to cover. In some cases where the power company plans have been submitted, a head guy towards the tracks has been requested on the two outer poles of the adjacent spans. These combined with the guys mentioned in Section 10 effectually guard against mechanical troubles in the spans adjacent to the crossing span. His suggestion that there may be cases where it would be safer and better to have the power wires pass under the existing wire does not seem practical. Usually power companies object strongly to having any kind of a wire suspended over their circuits; and certainly were I in charge of the construction force of the railroad company I would not care to have my men stringing telephone or signal wires over a live high tension transmission line any more than I think the power company's engineers would like to have railroad line crews so engaged.

His objection to paragraph 20 probably comes from a hasty reading of the said paragraph.

The objection to paragraph 25 does not seem to be well taken since the paragraph states distinctly "of the interconnected link type or its equivalent." It is doubtful that any cemented type of insulator will stand a rifle ball and not drop the line, whereas an interconnected insulator, especially if located a considerable distance from the power house, can be completely shattered and not drop the line; furthermore since these insulators are specified for only a very few spans of the whole transmission line, their unit cost may be many times that of the other insulators used and not increase the total line cost materially.

His objection to paragraph 26 possibly will disappear if the provisions of this paragraph are taken into account in connection with paragraph 29. The size of the conductor specified for the lower voltages in paragraph 27 was intended to cover distribution circuits such as are commonly used in this section of the country where No. 6 copper has been found satisfactory. It is not usual to use wire of this size in long distance transmission line work except for unimportant branches. In these cases it is hardly likely that sufficient current to burn off a No. 6 copper wire could be forced through it.

He states that he is not quite sure what paragraph 32 means. Perhaps its meaning will be made clear by a statement of the fact that in the operation of the large net-work in Central California no form of automatic circuit breaker as yet developed has given satisfaction, and it is the custom to operate these circuits tied in solid to the power house without any automatic devices intervening. Under these conditions it is evident that a grounding of the conductor when it comes down will be of considerable value, though it has not been found in practice that any grounding device installed at a distance from the power house will burn off the conductor.

I am glad to have my attention called to the possible ambiguity in paragraph 35. Up to this time it never had occurred to me that anyone would think of adding the horizontal wind and the gravity forces in any other fashion than as a geometric resultant.

Mr. Fowles' suggestion that the railroad company shall hold periodical inspections of the power company's structures in the crossing span strikes me as being a good arrangement provided the railroad company does not thereby assume any legal responsibility whatever for the safe operating condition of the power company's structures.

His suggestion that the conductivity and diameter of the conductor at the crossing shall exceed that in the main line by at least 25 per cent does not seem to me necessary for such transmission circuits as are operated in this part of the country, for the reason that it is practically impossible for any generating system to force into a net-work enough current to fuse any wire that is used. If any strengthening of the conductor at the crossings is needed, therefore, the reasons are purely mechanical, in which case it is proper to increase the ultimate strength of the section by a certain per cent, (say 25 in order to be consistent), rather than to increase by a stated amount, the diameter of the conductor, the material of which is not specified.

For many years I have agreed with Mr. Thomas that it is impracticable to provide a single set of hard and fast specifications to cover all cases and have consistently endeavored to have every crossing contract brought up as a separate matter. The table which forms the last paragraph of the original paper will show how difficult and how cumbersome this procedure can become, and after a number of years experience it was found desirable to draw up a general set of specifications, such as are here presented, for the guidance of the power companies in submitting their plans; and to require of them the submission of the detailed plans and specifications called for in paragraph 2, and the notice specified in paragraph 3, so that the railroad company may have an opportunity to check the details. Should Mr. Thomas ever appear before the Southern Pacific Company as engineer for a transmission company about to install a crossing with the railroad company's right-of-way he will find that detailed plans and specifications will be required by the railroad company and that his designs will be most carefully checked before the crossing contract is signed. In an organization less complete and less comprehensive than that of the railroad company this precaution might be neglected; but the Harriman lines organization is more military in form than is usually found in commercial enterprises. The division superintendents are held personally responsible for all such matters and they would no more dare permit an unauthorized crossing to be installed and maintained over their lines than would a subaltern manoeuver his command independent of the orders of his superior officer.

Mr. Thomas considers that the guys installed should be included in the calculations of the strength of the structures. Doubtless this is necessarily so in the case of the wooden pole construction, otherwise the structure becomes bulky beyond all reason; but in the case of steel structures it would seem desirable not to include the guys in the structure calculations but to have them as an additional safeguard.

Mr. Thomas' objection to the requirements of paragraph 23 does not seem to me to be well taken because the cost of a large insulator on possibly two or three spans of a long line is certainly out of all proportion to the cost of possible damage of a single failure of the transmission line at this point. In the East it may be an open question whether the interconnected link type of suspended insulator or the concentric type is really safer in preventing the dropping of the line in case of trouble, but experience in the West has shown distinctly that inter-link connection of this kind will not burn off in case of line trouble, unless such connections are very near the power station.

It is rather curious that Mr. Thomas should find in paragraph 26 an excessive requirement while Mr. Mershon finds the same paragraph to be too lenient.

I cannot agree that paragraph 27 should be re-worded to permit of well galvanized steel. Under no conditions, especially around sea-fog belts, should galvanized steel conductors of any kind be permitted to cross the railroad company's right-of-way.

Mr. Thomas is the only engineer so far who has objected to the provisions of paragraph 36. A conductor strung with a factor of safety of 2½ will be found to lie in a very flat curve, much flatter than is usually met with in practice. A safety factor of even 3½, such as is called for in the specifications, gives a reasonably flat curve, and in many cases the ordinary line construction as installed at ordinary temperatures, shows much higher factors of safety than are herein required. The requirement of paragraph 36 is intended to cover excessive strains produced by low temperatures or high winds.

I regret that Mr. Mershon's paper "Transmisison Line Crossings over Railroads"—*Railroad Gazette*, Feb. 7, 1908, and Mr. Fowles' paper presented two years ago before the Association of Railway Telegraph Superintendents, were unknown to me before these specifications were written—first, that I might have had the advantage of their experience, and second, that I might publicly have given them credit for such information from these papers as may be found in the specifications.

In conclusion I have to express my obligations for assistance to Mr. E. B. Katte, chief engineer, Electric Traction, New York Central Lines, and also to Mr. Joseph T. Richards, chief engineer of Maintenance of Way of the Pennsylvania Lines, both of whom have favored me with copies of their standard specifications.

A paper presented at the 249th meeting of the American Institute of Electrical Engineers, New York, May 17, 1910.

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METAL FILAMENT LAMPS

BY JOHN W. HOWELL

The first commerical metal-filament lamp was the osmium lamp, the filaments of which were made of osmium. They had a good commercial life at 1.5 watts per c-p., and were used in considerable quantity in Vienna and Berlin where they were made. They were not shipped to distant points, as the filaments were very fragile, and the metal osmium was so valuable that it was desirable to recover all the lamps after they had burned out.

The tantalum lamp appeared on the market in Germany in 1905 and in this country in 1906. The filament is drawn tantalum wire. This wire has a tensile strength greater than steel; it has a very high melting point, about 2800 deg. cent. according to Drs. Waidner and Burgess. It has radiating characteristics which make it an efficient light giving body. These qualities make it an excellent metal for use in filaments and these lamps have good commercial lives at 2 watts per c-p.

The strength and flexibility of the filament prevents breakage in shipment and adapts the lamps for use wherever they are subject to handling or rough usage of any kind. This valuable quality has enabled the use of tantalum lamp to increase rapidly while in direct competition with the tungsten lamp which operates at a much higher efficiency. The physical structure of the tantalum wire changes with use; it loses its smooth uniform surface and becomes rough, offset and brittle. This change takes place more rapidly on alternating current than on direct current. The cause of it is not definitely known.

Tungsten lamps were first placed on the market in this country about the beginning of 1907. They were sold in Europe in September 1906. The development and production of these lamps since that time has been very rapid, and in 1909 about 10,000,000 lamps were sold in the United States. This great commercial success of the tungsten lamp and the very interesting physical characteristics of the tungsten filament are the reasons for the presentation of this paper.

Tungsten lamps when first introduced were rated at 1.25 watts per c-p. The announcement of this figure created an immediate interest in the lamp; lamp users anticipated a great reduction in their bills for current; current sellers feared this same reduction; lamp engineers and those with scientific interest in lamps were most keenly interested, for to them a lamp with normal life at 1.25 watts per c-p. meant a lamp over 200 times as good as the standard carbon lamp. This figure represented to them the relative quality value of the new lamp when compared with the old standard carbon lamp.

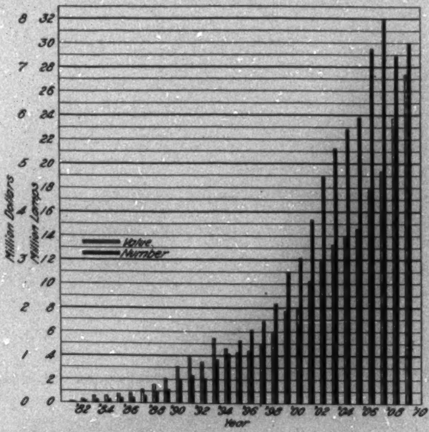

FIG. 1—Showing value and number of incandescent lamps produced annually by one manufacturer since 1881. The values for 1909 cover 11 months

Those who have used tungsten lamps with the object of reducing their bills have done so successfully, for if tungsten lamps are used to replace carbon lamps, candle for candle, a very material economy is effected and also much better lighting secured due to the much better color of the light and its much greater uniformity throughout the life of the lamp. Other users of the tungsten lamp have utilized the superior efficiency of the lamps to greatly increase the amount of light used while keeping the expense about what it was previously. Generally, however, a course between these two has been followed, the amount of light being materially increased and the cost of lighting also reduced; and experience has demonstrated that at current prices for electricity and lamps, the tunsten lamp will give much more light than will carbon lamps and at the same time reduce the cost of lighting.

The fears of current sellers that their income would be reduced by the introduction of tungsten lamps have not been realized, on the contrary, their income has been increased by the rapid extension of their business into new fields which were opened by the superiority of the new lamps, and by the availability of the larger sizes of lamps which, with carbon filaments, were not successful.

The first tungsten lamps sold in this country were high candle-power, thick filament lamps. There were two reasons for this: the filaments were more easily made than were thinner filaments, and the field of high candle-power lamps had been very imperfectly filled by carbon lamps. These early lamps consumed 100 watts and gave 80 candle-power; they gave us what we did no have before, good incandescent lamps of high candle-power, and they extended the use of incandescent lamps into an unoccupied field. Since that time both higher and lower candle-power lamps have been developed and the adaptability of tungsten to the making of all sizes of filaments has been fully demonstrated. Lamps are now on the market using currents as low as 0.15 ampere and as high as 10 amperes in a single filament.

Tungsten has been a boon to the pocket battery flash light business, in which lamps are now used consuming only 0.4 of a watt. Lamps using 500 watts and giving 400 c-p. are used in large numbers and some 1000-c-p. lamps have been made.

Lamps of the 220-volt class are also made. They require filaments twice the length of those required in 110 volt lamps, and they are therefore more liable to breakage, and are shorter lived at the same efficiency, than are the lamps of standard voltage.

Street series lamps taking from 3½ to 10 amperes and from

6 to 20 volts have short thick filaments and are very long-lived and satisfactory lamps.

Tungsten is one of the heaviest metals known, having a specific gravity of about 20. Its melting point is over 3000 deg. cent. according to Drs. Waidner and Burgess, which is higher than that of any other known metal. Its radiation characteristics are very favorable for its use as a light-giving source, for it possesses the quality called selective radiation, a relative term which implies that the proportion of its total radiations which are in the visible spectrum is greater than that of other substances which are considered normal.

The superior efficiency of tungsten lamps is due to these physical characteristics of the metal tungsten; namely, its ability to remain stable at a very high temperature, and its ability when at this high temperature to emit more than the normal proportion of its radiations in the visible spectrum.

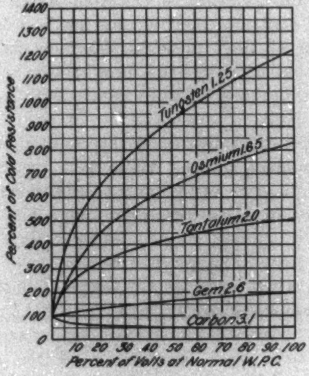

FIG. 2

Tungsten has other interesting characteristics; while its melting point is very high it oxidizes at a very low temperature—(about 300 deg. cent.). It also softens at a very low temperature, and filaments which are easily broken when cold can be bent permanently into any desired shape at a temperature below the oxidizing point. This characteristic is taken advantage of in making many filaments of special form, especially in making low voltage lamps; many filaments of spiral or helical form are made by winding straight pieces of filament on hot mandrels. Similar forms of filaments when made of carbon must be made in the desired form before carbonization.

The change of resistance with voltage in a tungsten filament is very interesting, especially when compared with a carbon filament. The specific resistance cold of carbon is 800 times that of tungsten and at normal working temperature it is 33 times that of tungsten.

The low specific resistance of tungsten is a disadvantage in making high voltage lamps, making it necessary to use very long thin filaments for these lamps. The length of filaments for 120-volt lamps ranges from 450 mm. for 20-watt lamps to 1400 mm. for 500-watt lamps. The disposal of such long filaments within the proper sizes of bulbs has necessitated a great advance in the art and science of lamp making. This advance has been made, and lamps of standard voltage are now made ranging from 20 watts and 16 c-p. to 500 watts and 400 c-p., all of which are well designed and of good quality.

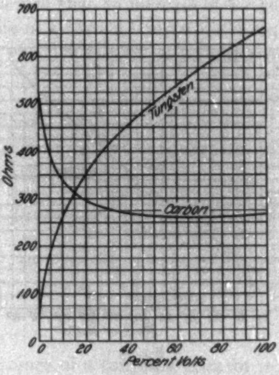

FIG. 3

For low-voltage lamps this low specific resistance is an advantage, giving more desirable dimensions of filaments for such lamps. This advantage has caused a considerable increase in the use of low-voltage lamps for many purposes in connection with storage batteries, and has led to the introduction of a residence lighting systems using 27 and 60 volt lamps, which are used with compensators or transformers on ordinary alternating-current circuits. These lamps have shorter and thicker filaments than lamps of standard voltage and the same candle-power. If filaments of the same diameter are used the filament will be one-quarter as long and give one-quarter the candle-power of the 100-volt lamps; thus, with the same filaments which are used in 20-watt, 100-volt lamps, lamps of 25 volts using 5 watts and giving 4 c-p. are made. These low candle-power lamps are very desirable in residence lighting in places requiring only a little light, and in chandeliers and clusters in which ornamentation is required as well as illumination.

If we compare lamps of equal candle-power, the 25-volt lamps will have filaments 0.4 as long and 2.5 times the diameter of those in 100-volt lamps, and the 25-volt lamps will be less easily broken by rough handling and will give longer life at the same efficiency. This longer life is due to the greater diameter and shorter length of the filament, for a thicker filament is less affected by minute imperfections, and a shorter filament has proportionately less chance of containing such imperfections.

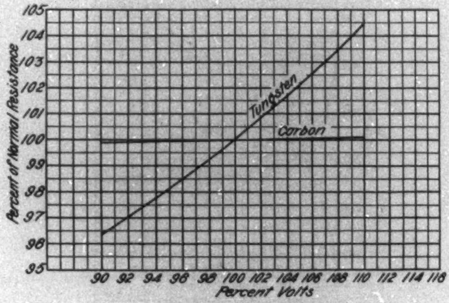

FIG. 4

Many lamps are now used in automobile headlights. These lamps have short thick filaments, which are not broken by the vibrations or jars to which they are subjected, and are very convenient sources of light. Ten-candle-power lamps in good parabolic reflectors give a very satisfactory light. These require 12 watts each, and ordinary storage batteries are well adapted for their use.

These resistance characteristics affect the rates of change of the candle-powers, efficiencies and lives of these lamps with changes of voltage, and curves are given showing the relative resistance changes of carbon and tungsten for a small range of voltage above and below the normal operating voltages of the lamps.

These curves show that in a tungsten filament an increase in voltage is met and partly counteracted by an increase in resistance, while in a carbon filament the resistance remains practically constant; consequently any increase in voltage produces less increase in watts, less increase in candle-power and less decrease in life in a tungsten filament than in a carbon filament.

It will be observed that an increase of 3.7 per cent in voltage will halve the life of a carbon lamp while it requires an increase of 5.2 per cent to halve the life of a tungsten lamp

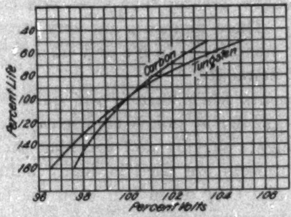

FIG. 5

The cold resistance of a tungsten filament is only one-twelfth the resistance at normal operating temperature, consequently when first connected to the circuit the current is for an instant much greater than the normal current. This excessive current is of sufficient duration to cause an instantaneous rise in candle-power, which is higher than the normal candle-power; this effect has been called overshooting.

Tungsten filaments as generally made today consist of an agglomeration of fine particles of metallic tungsten. These particles are sintered or welded together by raising the filaments to a very high temperature in a reducing atmosphere. This sintering is made as complete as the limitation of our knowledge of the art permits, and while great improvements have been made in this matter the best filaments are still more fragile than are carbon filaments. This fragility has been the greatest obstacle met with in the introduction of tungsten lamps, and in the beginning, when filaments were much more fragile than they are to-day, and when people had not learned the degree of care necessary in handling them, and when prices were very high, this weakness prevented many people from using the lamps. Now, filaments are much stronger, people have learned to handle the lamps carefully and prices are lower, so that the sales of tungsten lamps are increasing rapidly.

Flexible mountings for the interior structure of the lamps, which protect the filaments to a considerable degree, have been designed, and many lamps for railway car lighting and other special service are now being made, which have these flexible supports, to prevent breakage of the filaments in shipping and also in use.

The latest development which has been publicly announced is the drawn tungsten wire filament. This drawn wire has very great tensile strength, greater than steel, and can be drawn to any desired size. These filaments are very strong and are not injured by rough handling. In life and efficiency they are fully equal to pressed filaments.

Tungsten filaments when burning are quite soft and plastic and must be supported at points sufficiently near together to prevent the filaments sagging and touching each other or the glass. Spring supports are used in many lamps designed to prevent sagging and they do in fact keep the filaments nearly straight under all circumstances. These supports prevent the filaments being attracted over against the glass and being broken by static electricity which is a frequent cause of trouble with carbon lamps.

The variation of light from a filament due to the variation in current caused by the successive impulses of an alternating current depends upon the heat capacity of the filament, the heat radiating characteristic and the resistance characteristic. Tungsten has a specific gravity, about 10 times that of carbon and a specific heat one-fifth as great, so the heat capacity of a tungsten filament is about twice that of a carbon filament of the same dimensions. The heat radiating characteristic of tungsten is better than that of carbon because at a given temperature it radiates heat less rapidly than does carbon.

The resistance characteristic of tungsten is also more favorable than that of carbon for the retention of energy and heat as the current wave recedes. All these physical characteristics of tungsten are therefore better than those of carbon in respect to the retention of heat, and they all tend to make the flicker of tungsten lamps less than of carbon lamps of the same size filament.

The actual diameters of tungsten filaments, however, are much smaller than those of carbon filaments of the same candle-power lamps, and this more than offsets the advantages of the other characteristics, for the flickering of tungsten lamps is greater than that of carbon lamps of the same candle power, while it is much less for lamps with the same size filaments.

The flicker of a 25-watt tungsten lamp on a 60-cycle circuit may be observed by standing with your back to the lamp and moving a pencil rapidly back and forth, but I have been unable to observe this flicker by ordinary observation.

The flicker of a 40-watt tungsten lamp on a 60-cycle circuit is scarcely perceptible on a moving pencil.

LAMP TESTING

Lamp testing is an absolutely necessary adjunct to lamp making, and it is also a very necessary adjunct to proper lamp using. In order to determine the relative quality or value of different lamps, it is necessary to compare their lives at the same watts per candle-power or else to know the law of the relation of lives of lamps to their watts per candle-power, and I know of many cases in which inventors and investors have deceived themselves by judging the value of lamps when they did not know the rate of variation of life with efficiency, or the value of the time element in a test on a lamp.

From the results of experiments made over twenty years ago it was deduced that the lives of lamps at different candle-powers varied inversely as the 3.65 power of the candle-power. These experiments were made on lamps with untreated bamboo filaments. When treated carbon filaments came into use a great many experiments were made to determine whether or not this same exponent was true for them. The conclusion was that the same exponent should be used for both types.

Again when metal filament lamps became established the same question arose, and now comparisons have been made upon large numbers of lamps at different candle powers, each comparison being made between lamps of the same type, and the result of these comparisons indicates that the same exponent which is used for carbon filament lamps is also the proper one for lamps with metal filaments. In order to determine such a law it is necessary to make comparative tests upon a great many lamps, for it is impossible to get lamps so perfect that they each show the proper relative life to all the others. Averages must be used, and the law must be an empirical one. The exponent we have determined may simply indicate the relation between lamps of the usual degree of imperfection, but its persistence for so many years is remarkable, and we believe that it applies to all types and sizes of lamps which are well designed and well made.

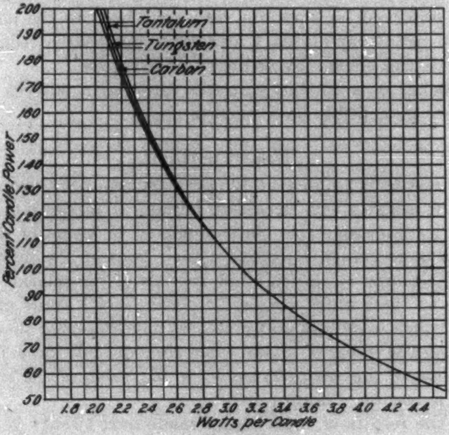

FIG. 6

From this relation between life and candle-power we can determine the relation between life and voltage, current, watts, or watts per candle-power. The relation between life and voltage or current depends upon the resistance characteristic of the filament and as different types of lamps have very different resistance characteristics, a different relation will be found for each type, and these relations are very little used.

The relation between life and watts or watts per candle-power is very nearly the same for all different types of lamps, because the relation of candle-power and watts per candle-power is nearly the same for all types. But as it is not quite the same it is customary to refer all life relations to the candle-power curve of the lamp for we consider this relation the same for all kinds of lamps.

LIFE FACTORS OR PER CENT LIFE OF TUNGSTEN LAMPS AT VARIOUS WATTS PER C. P.

Watts per c.p.	0	1	2	3	4	5	6	7	8	9
0.1	—	—	—	—	—	—	—	—	—	—
0.2	—	—	—	—	—	—	—	—	—	—
0.3	—	—	—	—	—	—	—	—	—	—
0.4	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.13	0.15
0.5	0.17	0.20	0.23	0.26	0.29	0.33	0.37	0.42	0.48	0.54
0.6	0.61	0.70	0.80	0.91	1.03	1.15	1.28	1.42	1.57	1.74
0.7	1.93	2.13	2.34	2.56	2.79	3.03	3.30	3.60	3.93	4.30
0.8	4.71	5.15	5.62	6.13	6.69	7.31	8.00	8.77	9.63	10.60
0.9	11.70	12.60	13.65	14.65	15.70	16.75	17.85	19.00	20.20	21.50
1.0	23.00	24.50	26.10	27.80	29.50	31.30	33.20	35.20	37.30	39.50
1.1	41.80	44.70	47.65	50.65	53.75	57.00	60.75	64.60	68.55	72.60
1.2	76.80	80.85	85.20	89.85	94.80	100.00	106.50	113.30	120.40	127.80
1.3	135.60	143.00	151.00	159.00	167.00	175.00	184.00	193.00	202.00	211.00
1.4	221.00	231.00	242.00	253.00	264.00	275.00	286.00	298.00	310.00	322.00
1.5	335.00	349.00	363.00	377.00	392.00	407.00	423.00	440.00	458.00	477.00
1.6	496.00	512.00	531.00	552.00	572.00	595.00	617.00	640.00	666.00	690.00
1.7	717.00	746.00	776.00	807.00	839.00	872.00	905.00	938.00	972.00	1007.0
1.8	1043.00	1081.00	1120.00	1160.00	1201.00	1243.00	1285.00	1327.00	1370.00	1413.00
1.9	1457.00	1510.00	1564.00	1619.00	1675.00	1734.00	1797.00	1864.00	1935.00	2010.00
2.0	2089.00	—	—	—	—	—	—	—	—	—

This table is made for use with metal filament lamps. It shows their lives between 0.4 and 2 watts per c-p. in percentage of their life at 1.25 watts per c-p. This table is very useful in interpreting life tests made at various watts per candle-power.

Metal-filament lamps last so long when tested at 1.25 watts per c-p. which is their normal rating, that it is customary to test them at higher efficiencies. Tests at one watt per c-p. are usually made; many tests at 0.75 watt per c-p. are made when quick results are desired, and daily factory tests, outside the life-test department, at double voltage, are very valuable when properly interpreted.

All tests comparing different types of lamps should be made on the basis of their spherical candle-powers, for the ratios between the spherical and horizontal candle-powers of lamps is sufficiently different to introduce very considerable errors if they are compared on the basis of their horizontal candle-powers, as is quite generally done.

Tungsten lamps of the ordinary 110-volt type have a spherical candle-power which is 0.785 of their horizontal candle-power, and when taking 1.25 watts per c-p. on the basis of their horizontal candle-power are taking 1.59 watts per c-p. on the basis of their spherical candle-power.

Many lamps for 63 volts are used for train lighting, and these lamps have a spherical candle-power which is 83 per cent of their horizontal candle-power. When taking 1.25 watts per c-p. on the usual horizontal rating they are taking 1.5 watts per c-p. on basis of their spherical candle-power. If life tested at 1.25 watts per c-p. horizontal, these lamps should have 335/477 or 0.7 as long life as a lamp of the 110-volt class having the same diameter filaments and also tested at 1.25 watts per c-p.

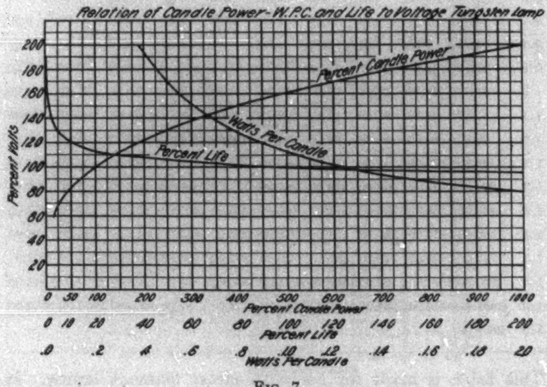

FIG. 7.

These lamps are tested at 1.25 watts per c-p. horizontal, and appear inferior to similar lamps of standard voltage, thereby suffering from an improper comparison.

The relation between horizontal and spherical candle-power depends upon the arrangement of the filaments in the bulb. As tungsten lamps generally have a number of simple loop filaments arranged in series, the relation will depend upon the height and spread of the filaments; the number of filaments in a bulb does not affect it.

DISCUSSION ON "METAL FILAMENT LAMPS", NEW YORK, MAY 17, 1910.

Clayton H. Sharp: I would refer for a moment to the importance of the tungsten lamp in street lighting. At the present time it would seem that our older illuminants for street lighting are on the decline. The arc lamp, as we have it, is being superseded by the more powerful arc lamps which have more recently been produced. The series incandescent lamp with the carbon filament, a lamp which never was very satisfactory for its purpose, has been most certainly pushed aside by the tungsten lamp. Not only this, but the advent of the tungsten lamp with its high efficiency and long life and favorable color has enabled the electrical engineer to go into fields of street lighting which previously have been practically closed to him, and which have been the exclusive domain of other less convenient and less satisfactory illuminants. I wish to point out further that there remains now the next stage, which is to provide means for utilizing more efficiently and satisfactorily the flux of light which the tungsten lamp produces in order to extend its usefulness in the range of street lighting still further. Such plans have been under consideration, and I recently had the pleasure of presenting to the Illuminating Engineering Society the details of a form of reflector by which the light which under ordinary circumstances is wasted by being thrown to the heavens, or thrown to the sides of the streets where it is not wanted, is directed into the dark portions of the street, midway between lamps, where such additional illumination is most desired. Along these lines I think the next step in progress is to be made.

FIG. 1

I wish to refer also to another feature of the tungsten lamp which is intimately connected with the over-shooting of current at the moment the circuit is closed, due to the large positive temperature coefficient. Another thing results from this, which is perhaps of academic interest only and that is that the change in resistance of the filament during a cycle of alternating current necessarily lags somewhat behind the change in electromotive force, on account of the thermal capacity of the filament. Since the resistance of the filament lags behind the e.m.f., the current in it must lead the e.m.f. by a certain small amount and the lamp is not strictly non-inductive, but behaves as if it possessed a certain electrostatic capacity. In an attempt to demonstrate this effect, an e.m.f. having an extremely peaked wave was built up using the harmonic synthesis set of the Electrical Testing Laboratories. This wave form was selected so that the effect might be exaggerated as much as possible. Wavemeter curves were taken of the e.m.f. and of the current in a 25-watt 110-volt tungsten lamp with a frequency of 25 cycles per second. This frequency was chosen as being as likely as any to give a maximum effect. Too high a frequency would not permit the filament to cool enough during the zero portion of the wave, whereas, if the frequency were too low, the rate of change of e.m.f. on the lamp would be too slow to enable the effect to be seen. The curves of current and electromotive force are shown in Fig. 1, and the phase angle between them, though small, can be clearly appreciated. In order to make the difference more effective, the tungsten lamp and the carbon lamp were connected as the two arms of a Wheatstone bridge, while the wavemeter was used to determine the wave form of the electromotive force across the diagonal of the bridge. This gave a wave which is shown in Fig. 2.

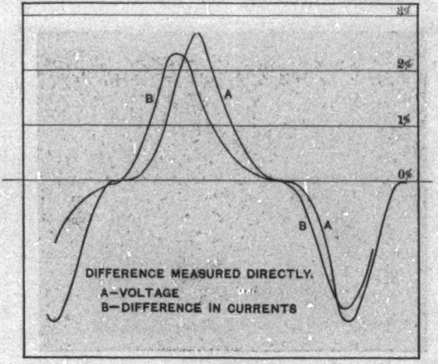

FIG. 2

The resistance variation of the tungsten lamp during the cycle was measured, and the minimum value of resistance was found to be about 10 per cent less than the maximum value. The power factor as roughly calculated was found to be 0.99975.

John B. Taylor: Dr. Sharp has just been enlarging on what he calls a feature of merely technical interest, and that is, a slight improvement in power factor due to the substitution of tungsten lamps for carbon lamps.

I think there is a much more practical point directly connected with this matter of positive temperature resistance coefficient, in the fact that the lamp cold takes a much larger current than when in normal service. Resistance curve, Fig. 3, of Mr. Howells paper, shows a cold resistance of 50 ohms, and a hot resistance of 650 ohms, or a little more than thirteen times greater. An oscillograph actually shows a peak value of current about eight times the normal. This difference is due partly to the fact that the lamp has risen slightly in temperature before maximum deflection of the oscillograph, but mainly to reactance and resistance in the circuit. In practice the initial current may be five to eight times the normal value. Usually this large rush of current is not important, but imagine the case of a general shut down on a large interconnected Edison system. Even with carbon lamps there is difficulty in getting under way again, for the reason that all the different substations cannot be connected at the same moment, and the ones that come in first get more load than they can carry. This difficulty with carbon lamps, will be more serious with tungsten lamps. In an isolated plant, if the main breaker opens and it is attempted to throw in the load again, at this one switch, instead of breaking up the system at feeder switches, the generator will be momentarily overloaded five to eight times, depending on line drop and other matters. This may not be a serious matter with some machines, but it cannot be dismissed without investigation. Fuses are not liable to blow on account of the short interval of time during which the current has the large value, but circuit breakers with less time lag may be tripped, and the excess load may cause mechanical troubles or flashing at the commutator. These points deserve consideration.

Another point I want to bring out is more academic. Mr. Howell says: " This excessive current is of sufficient duration to cause an instantaneous rise in candle-power, which is higher than the normal candle-power; this effect has been called " overshooting ." I believe I am responsible for the term " overshooting " having used it two years ago when describing the effect in one of the technical periodicals* with photographic records demonstrating that it is a real " effect " and not a mental impression. The point I want to make is that the positive temperature resistance coefficient and excess current will not explain " overshooting " unless it can be shown that there is a time

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***Electrical World*, April 25, 1908 and May 16, 1908.

lag between temperature of a body and its electrical resistance. The temperature is going up very rapidly, perhaps 100,000 degrees cent. per second, but that is no reason why, merely because it is rising so fast, it should continue rising beyond the ultimate temperature determined when balance is reached between energy radiated and conducted away and energy supplied. The only thing I suggested, when I showed the photographic evidence of overshooting was that it might be some secondary action, possibly connected with gases absorbed by the filament, which before begin driven out might modify the resistance for a very brief time. I think the present tungsten lamps do not show the "overshooting" to the extent that the early ones did.

Farley Osgood: I think I may be pardoned if I bring up a point which is purely financial or commercial. The discussion so far has been confined entirely to the physical side of the lamp, and the various problems, theoretical and practical, pertaining to its improvement in efficiency, but there is another point which to my mind is equally important, especially to the users of the lamp, who are quite as much to be considered as the makers of the lamp. Of course, the manufacturers advocate the use of the highest efficiency lamps of the metalized filament type, but my experience is that it is still an open question as to whether or not the metalized filament lamp is an economical proposition for an operating company using a million lamps or more per year. The product of metalized filament lamps of the not most perfect type, namely, all lamps except tungsten, is still so uncertain that the economical average life of such lamps does not from a saving standpoint warrant their introduction on a free renewal basis by operating companies. Most of the operating companies in the country have free renewals of the older type of carbon lamps among all consumers of electric current, and although the total average of metal filament lamps show such a life as to be equal to the carbon lamp, our investigation seems to show that such a result is brought about by the unusually long life of some of the lamps put under test. A few lamps will give extraordinarily long life, and a large proportion of lamps will give not so long a life in the life test, so that although the advocates of the use of this lamp, namely, the manufacturers, are able to show that these conditions are equal between carbon lamps and metalized filament lamps, the operating men are unable to realize it from a financial standpoint. If a greater portion of the lamps show shorter life, and the equal average life is occasioned by the abnormal continuance in service of a few lamps, the expense, from an operating company's standpoint, will increase greatly rather than remain the same. I think it is an open question whether the metalized filament multiple lamp should be used on a free renewal basis, unless the operating companies decide that it is desirable to spend a considerable additional sum for incandescent lamps for the sake of the various benefits which accrue to the consumer by the use of the metalized filament lamp.

In the street lighting service, the condition is almost entirely changed. The tungsten filament lamp can be safely said to average a life of 1500 hours, so that its use is equal to, or better than, the carbon series filament lamp; the renewals are less frequent per year, and the financial results, particularly on account of the lower current consumption, are beneficial to the operating company using tungsten lamps for series street lighting purposes. But I do not think these facts should be lost sight of in the consideration of a more modern or metalized filament type of lamp, and I do not think it amiss to bring out at this time some of the uncomfortable features of the metalized filament lamp as many of the consulting engineers of this Institute have before them for decision such problems for the companies which they represent.

William L. Nodell: I wish to add to the information which Mr. Howell gives concerning tungsten automobile headlight lamps. These are now made in candle-powers ranging from 10 to 25 and operate satisfactorily at the excellent efficiency of 0.8 to 1.0 watts per c.p. They are recommended to be used at 6 volts (3 cells of storage battery) though lamps suitable for other voltages are furnished.

Mr. Howell's paper may give the impression that the normal commercial rating of tungsten lamps is still 1.25 watts per c.p. This is no longer the case, the efficiency being better in lamps of 60 watts and higher, as may be seen from the table given herewith, showing the watts per candle-power and life obtained since the 3 voltage method of rating tungsten lamps has been established:

TUNGSTEN REGULAR MULTIPLE LAMPS FOR 100–125 VOLTS

Designation total watts	At top voltage			At middle voltage			At bottom voltage			
	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Watts per c.p.	Nominal mean horizontal candle-power	Hours useful and total life	Horizontal c.p. multiplied by this reduction factor = spherical candle-power
25-watt	1.33	18.8	1000	1.39	17.4	1300	1.45	16.1	1700	0.78
40-watt small bulb	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
40-watt large bulb	1.25	32.0	1000	1.30	29.9	1300	1.35	28.0	1700	0.77
60-watt	1.20	50.0	1000	1.25	46.5	1300	1.30	43.5	1700	0.78
100-watt	1.15	87.0	800	1.20	80.8	1000	1.25	75.2	1300	0.78
150-watt	1.15	130.3	800	1.20	121.1	1000	1.25	112.8	1300	0.78
250-watt	1.10	227.3	800	1.15	210.0	1000	1.20	195.0	1300	0.77

Figures furnished by the N. E. L. A.

The philosophy of the three voltage plan is that formerly applied only to gem lamps. Since May 1, 1910 this method of rating is applied to all incandescent lamps, tungsten, tantalum, gem and carbon. A lamp is no longer identified by candle-power and watts-per-candle power but is designated by watts; the efficiency at which it is to burn being determined by the selection of top, middle or bottom voltage. Exceptions to this general rule are miniature lamps and the 4 watt per c.p., series-burning railway lamp, which will be known, as heretofore, by their candle-power.

Referring again to Mr. Howell's paper regarding spring supports to prevent sagging of tungsten filaments; though molybdenum supports are being used for this purpose by some manufacturers, the alleged benefit to be derived is not sustained by the general experience of the majority of manufacturers who have, after exhaustive tests with every known method of support, finally adopted the copper hook at the tip end of the lamp as giving the greatest satisfaction, particularly in the 25-watt, 40-watt and 60-watt sizes. In the larger sizes with heavier filaments the spring support is still less necessary and in the 250-watt lamp practically all manufacturers employ a rigid support. For a time a center anchor was used in one make of 25-watt lamp but this is not now recommended, as the advantages expected are not borne out by experience.

I wish to call attention to a paper on "Tests of Tungsten Lamps", by T. H. Amrine and A. Guell, giving the results of observations on three types of lamps, two of German manufacture, the third American. The results in comparison with the two foreign lamps are very much in favor of the home product.

John W. Howell: There is one characteristic of the tungsten and carbon lamps which I have omitted to mention in this paper, and that is their relative candle-powers per unit of surface. We are all familiar with the intense brightness of the tungsten lamp, as compared with the old carbon filament, and we know that it is necessary to shade the direct light of the filament from our eyes, either by shades or frosted bulbs. As a matter of figures, the tungsten filament at its normal efficiency is giving twice as much light per unit of surface as the carbon filament at its normal efficiency. If the two lamps are placed at the same efficiency, the conditions reverse; the carbon filament is then giving twice as much light per unit of surface as the tungsten filament. This is an indication of one of the reasons of the efficiency of the tungsten lamp, because when you see a carbon lamp giving twice as much light per unit of surface as the tungsten lamp, there is a strong physical indication that the temperature of the carbon lamp is much higher than the temperature of the tungsten lamp, and it is a fact, at the same efficiency, a carbon lamp is much hotter than a tungsten lamp. When you examine the same characteristic for a tantalum lamp it is interesting, because the normal efficiency of a tantalum lamp is two watts per candle, and at that efficiency the light per unit of surface is the same as the carbon lamp, at 3.1. This marked difference between tantalum and tungsten indicates one reason for the poorer efficiency of the tantalum lamp.

G. S. Merrill, M. D. Cooper, H. D. Blake (by letter): It is well known that tungsten filaments, due to their positive temperature coefficient take more current at the instant of starting than after they become heated. The engineering department of the National Electric Lamp Association recently conducted a series of experiments to determine whether this initial current rush has the effect of decreasing the life of the lamps. Three lots of tungsten sign lamps, 6 lamps in each lot, were placed on test—the first lot was burned continuously, the second lot was flashed 3 times per minute and the third lot was flashed 30 times per minute. It was found that there was a slight decrease in life with the lamps that were flashed, but that this decrease was so slight as to be practically negligible. The curve of Fig. 1, plotted between frequency of flashing and the per cent of normal total life, shows a decrease of about 6 per cent in life up to 35 flashes per minute. For higher frequencies the life rises toward normal value. This test, due to the small number of lamps used, is not, of course, absolute proof that the initial current rush may not have a greater effect in decreasing the life, but it indicates that the effect is not as great as might be supposed.

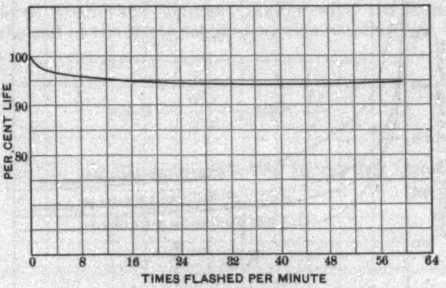


FIG. 1

That the above should be the effect becomes evident on consideration of the "cooling curves" given in Fig. 2. These curves show the per cent of cold resistance of tungsten lamps at various time intervals after the lamp has been turned off. If the lamp is allowed to cool completely before being again lighted, the initial current rush will be as severe as at the first lighting. If, however, it is turned on when the resistance is still considerably above cold value, the current will not rise to as high an initial value. For instance, if a sign lamp is flashed six times per minute (5 seconds on, 5 seconds off), it will be relighted when the resistance is still 2¼ times the cold value, and as the hot resistance is about ten times the cold value, we would expect only about one-fourth as great a rush of current as when the lamp had fully cooled.

Flashing at very high frequencies would correspond to operation on alternating current, which would give the same life as when burned without interruptions.

Mr. Howell's mention of spring supports brings up the question of the adaptability of tungsten lamps to burning in a horizontal position. The complaint is sometimes made that tungsten lamps do not prove satisfactory when burned horizontally because the filaments sag.

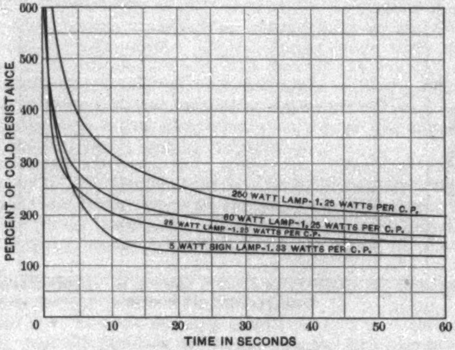


FIG. 2

The sagging filament in a horizontally burning lamp will conform closely to the catenary curve, for the filament is comparatively heavy and after continued heating will respond to the force of gravity nearly as well as a perfectly flexible string or chain.

The accompanying curves were derived on the assumption of this catenary curve. The equation of the catenary is:

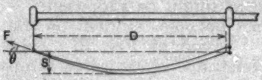


FIG. 3

$$y = \cosh x$$

and in this form the y intercept is 1. For a given distance, D, between supports, the sag will be

$$s = \cosh \frac{D}{2} - 1 \qquad (1)$$

$$\text{or the per cent sag} = \frac{100}{D}\,S = \frac{100\left(\cosh\dfrac{D}{2} - 1\right)}{D} \qquad (2)$$

Fig. 3 shows in an exaggerated manner, the way in which a filament will droop and as there shown, D is only the distance between the ends of the freely sagging portion of the filament. Due to the rigid weld at the base, the whole filament will not sag freely, hence D will not be the whole of the distance between supports.

The slope of the curve will be

$$\frac{d\,y}{d\,x} = \sinh x$$

The angle θ, which the filament makes with the horizontal through the end of the freely sagging portion will be given by the equation,

$$\tan\theta = \frac{d\,y}{d\,x} = \sinh\frac{D}{2}$$

If the weight of the filament is W, the supporting force F will be given by

$$F = \frac{W}{\sin\theta}$$

from which

$$\frac{F}{W} = \frac{1}{\sin\,\tan^{-1}\,\cosh\dfrac{D}{2}} \qquad (3)$$

Using the parametric equations (2) and (3), curve A of Fig. 4 was plotted, showing the "stress ratio", F/W, for any given sag.

When a lamp hangs vertically, the maximum force is equal to the weight of the filament, hence the above ratio is the same as the ratio between the filament stress when the lamp burns horizontally and that when it burns vertically.

To investigate the effect of contraction on cooling, it is necessary to get some relation between length of filament and corresponding sag.

The total length L is given by the equation

$$L = 2 \int_0^{\frac{D}{2}} \sqrt{1 + \frac{d\,y^2}{d\,x}}\;d\,x$$

$$= 2 \int_0^{\frac{D}{2}} \sqrt{1 + \sinh^2 x} \quad d\,x$$

$$L = 2 \sinh \frac{D}{2}\Big] \tag{4}$$

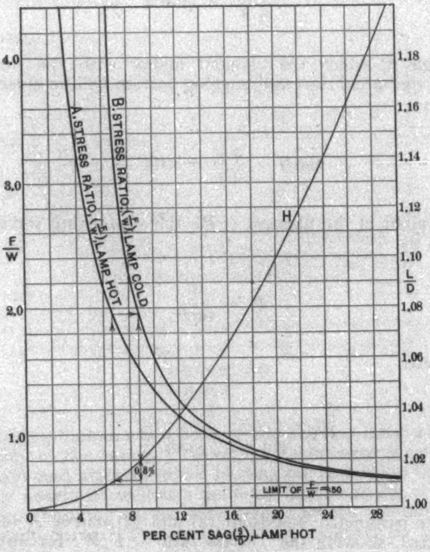


FIG. 4

Using this equation in connection with (2), curve H was plotted showing the per cent sag for a given value of L, expressed as a percentage of D.

A point on curve A shows the stress in a horizontally burning filament for a given sag when the lamp is burning. At the same point, the ordinate or curve B shows to what extent this stress is increased by the shrinkage of the filament on turning off the lamp. In deriving this second curve a shrinkage of 0.8 per cent was used, as determined by experiment. Curve *B* was derived from *A* as follows: For example, at 8.8 per cent, sag *L* is 102 per cent of *D*. On turning off the lamp, *L* decreases 0.8 per cent, hence the sag will be reduced to 6.8 per cent, corresponding to a stress ratio of 1.90, which is plotted over the "hot sag" of 8.8 per cent.

The curves show that a certain amount of sag is necessary if excessive filament stresses are to be avoided. If a lamp were so designed that when burning horizontally the filament would sag but 7 per cent, the stress would be 1.85 times as great as when burning vertically, and when turned off, the stress ratio would rise to 3.0.

The effect of burning a lamp is to cause the filament to disintegrate gradually. This disintegration, moreover, is not absolutely uniform, but is liable to localize at any weak points on the filament, if such there are. As the lamp continues to burn, the weak spots disintegrate more and more rapidly, till they can no longer withstand the imposed mechanical stress and a burnout results. It is therefore apparent that, although the filament as a whole could withstand a stress many times greater than its weight, yet, due to its non-uniform disintegration, an early burnout will be the inevitable result of insufficient sag and consequent high stress ratio.

A number of lamps, of the 25, 40 and 60-watt sizes and of the most recent design, showed from 10 to 15 per cent sag after they had burned for some time. The curves show that for this range of sag, the filament stress ratio, even when cold, will not rise above 1.60.

The curves cannot be rigorously applied to lamps larger than the 100 watt, for in these the filaments are larger and stiffer and do not sag freely.

The investigation of the flickering of incandescent lamps on alternating current can be separated into two divisions; first, the determination of the effect on the cyclic variation in candle-power produced by varying the size, length and material of the filament; and second, the determination of the relations between cyclic variation in candle-power, intensity of illumination, and "critical frequency" (or the frequency at which the sensation of flicker just disappears).

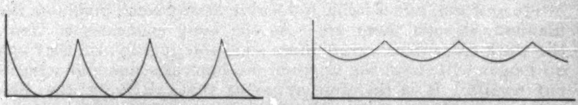
We have recently conducted some experimental work on the second division of the subject—the relation between cyclic candle power variation, illumination intensity and critical frequency. We found that for a cyclic variation *M*, equal to $\frac{\text{variation in c.p.}}{\text{max. c.p.}}$, and an illumination *I*, in foot candles, the critical flicker frequency *f*, in cycles per second (twice the current frequency) is given by the relation

$$f = 43\,(I\,M)^{0.13}$$

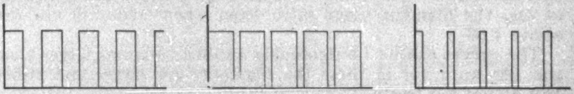
The constants in this equation were derived from five sets of data taken by two different observers, and the average deviation from the mean is about 7.8 per cent for each constant.

The cyclic variation in illumination was produced by a vane rotating at variable speed in a beam of light. In front of the vane was an opaque screen with a hole in it, the hole being covered with a ground glass diffusing plate. By using vanes of different sizes, we obtained different ratios of variable to maximum illumination. The flicker was viewed on the test plate of an illuminometer placed eight inches from the ground glass. Simultaneous readings were taken of the illumination and of the speed of the rotating vane at which the flicker sensation disappeared.

The rotating vane gives a cyclic variation in illumination about like the following curves:



Experiments show that the cyclic variation in candle-power of a lamp on alternating current very closely approximates a sine wave raised up above the axis. Dr. Kennelly conducted some experimental work on flicker using cyclic light waves of the following shapes, and his results tend to show that the critical frequency is a function only of the maximum and minimum illumination, and is not affected by wave shape. His equations when put in the form expressed above, agree closely with ours. His results were published in the 1907 Proceedings of the National Electric Light Association.



The question of flicker comes up most often in connection with the operation of metal filament lamps on 25 cycle current. Letting f in the above equation be 50 (the flicker frequency corresponding to a current frequency of 25 cycles) there results

$$IM = 3.18$$

The table below is computed from this equation and shows the maximum permissible cyclic variation in candle-power allowable with various intensities of illumination. If in any case the variation is greater than that given in the table, a flicker will be perceptible. With an illumination of less than about 3 foot candles, flicker will not be discernible, no matter how great the cyclic variation.

Intentisy of illumination I	Maximum allowable cyclic variation on 25-cycle current M
10	31.8%
8	49.8
6	53.0
5	63.6
4	79.5
3.18	100.0

We thoroughly agree with Mr. Howell in his statement that lamp testing is absolutely necessary to lamp making and also a very necessary adjunct to proper lamp using, but one should not understand from Mr. Howell's remarks that the necessity of testing in any case extends beyond the manufacturers or other thoroughly equipped lamp testing bureaus. Unless lamps are tested under the most rigid conditions the results are worse than useless and this applies with particular force to tests run at higher than normal efficiencies in order to shorten the time of testing. In such "forced" testing the effects of errors in test voltage are multiplied many times in reducing the results to normal performance and if the forcing is carried to an excessive point the extremely high temperature produced may create abnormal conditions which tend to make the lamps appear better or worse than tests at actual rated efficiencies would have indicated. Do not understand for a moment that we wish to undervalue the importance of forced testing, for when conducted under proper conditions and with proper knowledge of the limitations and errors to which it is subject, the forced test forms a very valuable means of rapidly attaining comparative results and has proved of inestimable service to the manufacturers. The Engineering Department of the National Electric Lamp Association has been devoting a great deal of study to the forced testing of metallic filament lamps, principally because the extremely long life attained at normal efficiencies served to severely tax the testing capacity and because urgent demand was being continually made by the factories for quicker test results. In spite of the fact that this problem has been before the engineers of the department for some time, no correction figures have yet been decided upon which can be regarded as final. Since Mr. Howell has brought the subject before you and as some may endeavor to proceed with forced tests upon the figures he has given, he will give some data in connection with this matter.

The earlier attempts to secure a correction figure for forced tests were based upon the average life of numerous lamps, run at various efficiencies. Tests conducted on such lines were not fruitful of results of the accuracy it was desired to attain. A study of the results of such tests, and previous experience with performance of the older and better known carbon filaments led to the following conclusions.

Steinmetz* has stated that "tungsten filaments do not ordinarily fail by evaporation as is the case with carbon, but by melting at some weak spot;" and also that "blackening of tungsten lamps is not gradual, as with carbon, but occurs simultaneously with impaired vacuum and appears rapidly." Our experience would indicate that there is a certain slight amount of normal blackening of tungsten lamps. The fact that this blackening deposit is found to consist largely of tungsten, and that the current after the initial rise tends to decrease gradually leads us to believe that the filament actually is vaporized to a limited extent.

A perfect filament would have a perfectly uniform temperature throughout practically its entire length. Near the supporting wires, the cooling effect due to these supports, would demand consideration. This filament could be conceived to be disintegrating at a uniform rate throughout its entire length except near the supports, with an ultimate result somewhat as shown in Fig. 5, which represents in an exaggerated way a short length of filament.

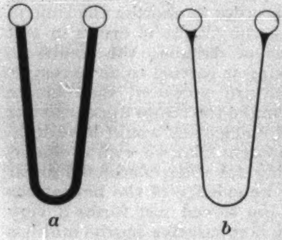


FIG. 5

The candle-power of such a filament when burned at a constant normal voltage would probably show a slight initial rise due to changes in the physical characteristics of the filament material and to changes in the condition of the residual gases in the bulb (which of course are at extremely low pressure). After an initial rise the candle-power would drop gradually at a diminishing rate, until the radiation within the limits of the visible spectrum had become incapable of producing the sensation of light. During this period the value of the current flowing through the filament would have changed in a somewhat similar manner to the luminous radiation, but even after the filament had ceased to emit visible radiation the current would still flow and the filament would never burn out.

The decrease in candle-power would be due essentially to two things:

1. The temperature would decrease as the filament material evaporated and the diameter decreased. Neglecting possible changes in physical characteristics after the initial changes already noted, the energy expended in the filament would decrease as the square of the diameter of cross section. Obviously the surface of the filament would decrease directly as the diameter, so that as the filament evaporated the energy expended

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* "Radiation, Light and Illumination" pp. 80, 81.

therein would decrease more rapidly than the radiating surface and the temperature would decrease.

2. The total radiating surface would be decreased. As a third, though secondary effect blackening of the bulb by condensation of evaporated filament material upon the interior surface would cause a decrease in candle-power of the lamp as a whole.

Such would be the performance of a filament without defect. In actual filaments defects exist and the magnitude of the defects is a variable quantity which follows to some extent the laws of probability for a given lot of lamps. For example, out of a large number of lamps started on life test under the same conditions, a few would probably fail rather early in life due to large defects or imperfections in the filament itself. As the burning continues the " mortality " rate would increase as the average size defects would begin to cause failures. Then with the number of lamps burning considerably reduced, the rate of failure would decrease, for there would then be left only lamps having defects of less than average size. Finally there would be left only a few lamps which would give a very abnormal life, because they might happen to be particularly free from imperfections in structure. During this period the candle-power would have been undergoing the general changes previously noted which may be illustrated by the actual performance curve obtained from a test of 115, 16-c.p., 3.5-watts per c.p. carbon lamps as shown in Fig. 6. The average total life to burnout of the lamps represented on this test was several times the so-called " useful life ", to 80 per cent of initial candle-power. The average candle-power corresponding to the average life gives us a means of judging the magnitude of physical imperfections which exist in the filament. On this basis it appears that at the present the carbon filament is more highly developed than

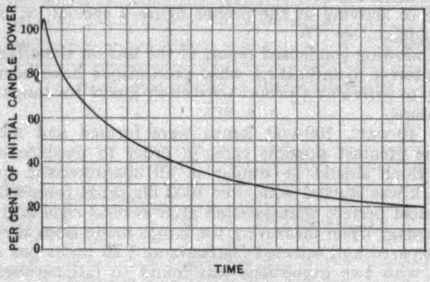

FIG. 6

the tungsten filament, inasmuch as the carbon lamps reach a relatively lower candle-power value before failure than the tungsten lamps. This shows that there is still room for enormous improvement in the tungsten filament and that there are possibilities for obtaining still higher efficiencies than those at present attainable.

From the above considerations, it was decided that the correction figure to be applied to the life of metal filament lamps burning at other than normal efficiency could be determined more accurately from the time required by lamps operating at various efficiencies to reach the same percentages of initial candle-power or of initial current than from the actual time to failure or burnout. This should be true whether the changes in candle-power and current are due entirely to disintegration of the filament or whether they result from some other physical change which takes place during life.

It is manifestly impossible to obtain results on a single individual lamp at more than one efficiency, consequently for the purpose of arriving at the proper figure a special lot of lamps were made.

The following condensed report of the test on these lamps will be of interest in indicating what precautions have been taken in order to arrive at a proper correction factor for tungsten filament lamps.

Fifty 40-watt, 109-volt lamps were formed and assembled with the greatest possible care, in order to produce a lot of lamps which should be similar in all characteristic qualities. The work was started with over 1000 filaments from which 200 of the most perfect were selected after several rigid and careful inspections. Upon measuring the lamps made from these carefully prepared and selected filaments at 1.25 watts per c.p. the voltage with two exceptions was found to fall between 108.8 and 109.2 volts inclusive, a range of but 0.4 volts.* Aside from indicating a close selection, this uniform rating simplified to a large extent some of the work of testing, and has, we believe, eliminated the possible source of several small errors.

The test was divided into five sets of ten lamps, which were burned on 60-cycle alternating current at efficiencies of 1.25, 0.97, 0.85, 0.75 and 0.67 watts per mean horizontal candle power respectively. According to the best correction figures available at the time the test was started each set was measured at approximately equivalent intervals. Readings were made with a contrast Lummer-Brodhun screen at rated voltage and

---

* If lamps can be made by commercial processes and in an ordinary factory which come within 0.2 of one per cent of the rating for which they were designed, it might be possible, by using more refined methods of manufacture, to produce a primary standard of light with tungsten filament.

An ordinary commercial lamp would not, of course, serve the purpose. It might, however, be possible to make a single loop lamp under rigid specifications as to size, length, and processes of manufacture of filament, dimensions of leading in wires, size and shape of bulb, etc., that could be exactly reproduced at any time. Such a lamp could be not only a primary standard, but an absolute standard as well, for it is well within the range of possibility to compute as well as measure the luminous intensity of such a source.

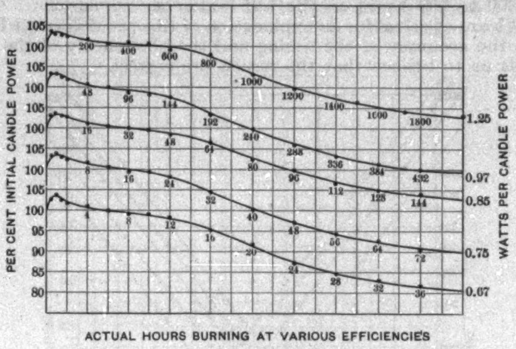

FIG. 7

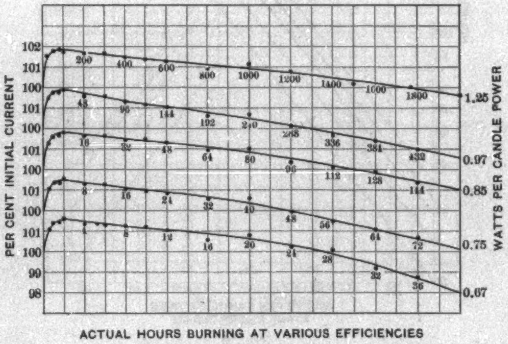

FIG. 8

all currents were checked in each instance with accurately calibrated standard laboratory meters.

Average candle-power curves for the various efficiencies, together with the actual hours burning, are plotted in Fig. 7, and average current curves for the same lamps are plotted in Fig. 8. We are able to show these only out to 2000 equivalent hours, at 1.25 watts per c.p., because the test is still in progress with over 80 per cent of the lamps still burning.

We wish to call attention to the peculiar shape of the candle power curves of Fig. 7. Their peculiarity is the unexpected maintenance of candle-power during the interval corresponding to 300 to 700 hours on the 1.25 watts per c.p. curve.

We are at a loss for an explanation of this peculiar curve form but the accuracy of the timing and the photometry of the test leads us to believe that the results are correct.

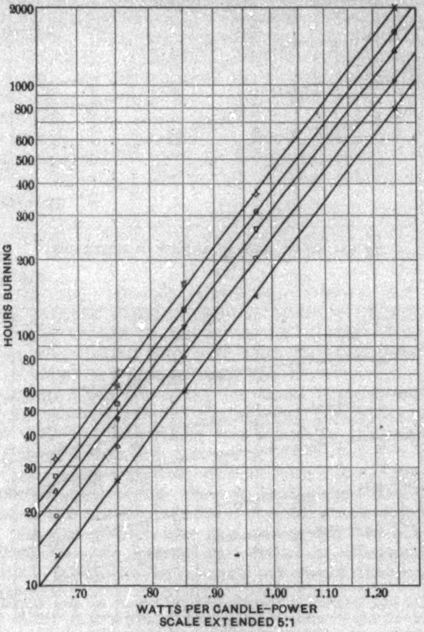

Fig. 9

From previous experience we assumed that the equation between life and efficiency is of parabolic form:

$$\frac{\text{Life}_1}{\text{Life}_2} = \left(\frac{\text{Watts per c.p.}_1}{\text{Watts per c.p.}_2}\right)^b$$

the object of this test being to determine the exponent *b*. In Fig. 9 and Fig. 10, we have shown several logarithmic graphs between watts per c.p. and hours life obtained by comparing the interval of time required to reach various percentages of the initial values of candle-power and current. The results show that the life equations for tungsten lamps conform very rigidly to a pure parabolic law over the range investigated. The candle-power curves and the current curves appear to give slightly different values of exponent *b*. We believe that the exponent derived from the candle-power curves is the more accurate, where total life values are to be determined. In Fig. 11 we have shown curves between the watt per candle-power life exponent, *b*, and hours burning at normal efficiency (1.25 watts per c.p.).

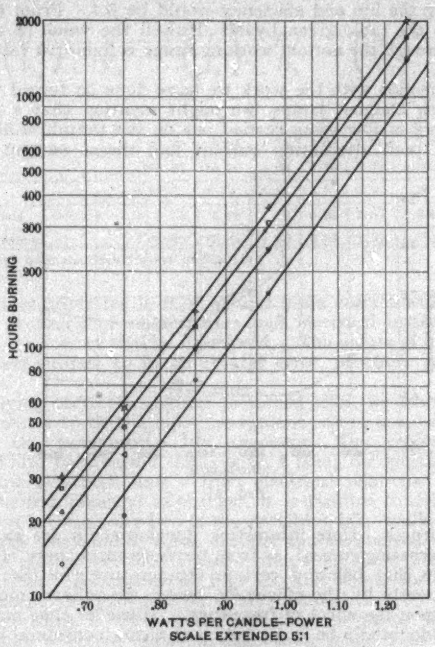

Fig. 10

The correction figure for tungsten filament lamps is still in some doubt, which may be evident from the results of the test previously described, and also from the fact that in his paper Mr. Howell seems to have used two different values for the exponent of the life-efficiency equation. Mr. Howell states that the life was found to vary universally as the — 3.65 power of the candle-power. This exponent was derived from experiments on lamps with untreated bamboo filaments, but he says it was later found to hold for treated carbon and metal filament lamps. If the candle-power is taken to vary as the 1.75 power of the efficiency, as careful work would indicate, the exponent connecting the life and efficiency would be 6.4. From the life factors in the table given by Mr. Howell the value of the exponent through the normal working range is found to vary from 6.7 to 6.8.

In connection with the work we have done on forced testing of tungsten filament lamps, we might mention that a similar line of work is now being carried out on the tantalum filament lamps on both alternating current and direct current for a similar purpose. Here interesting developments are expected on the alternating current, as from previous tests there is much to indicate that below a certain temperature the life is not affected greatly by the efficiency, being, we believe, more dependent upon the effect of frequency. However that may be, we will undoubtedly be in a position to throw considerable light upon the matter in the near future.

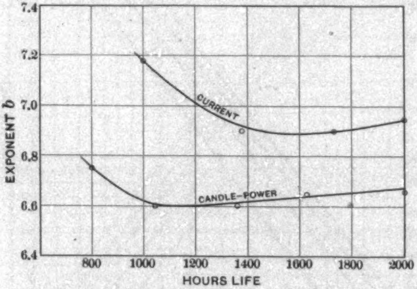

Fig. 11

As to the relation between life and watts or watts per candle power being very nearly the same for all different lamps we cannot agree. The exponent by which we express the relation between life and efficiency varies from 6.65 for the tungsten filament lamps to about 5.43 for untreated carbon. The first mentioned figure may be changed somewhat in view of later developments, but we find that the treated carbon, gem, and tantalum exponents, in so far as we have been able to determine them, are scattered between these limits.

In the table below are given our determinations of the exponents of the following equations, in which L = hours life, C = candle-power, W = total watts, e = watts per candle, V = voltage, I = current and R = resistance.

$$\frac{L_1}{L_2} = \left(\frac{C_2}{C_1}\right)^a = \left(\frac{e_1}{e_2}\right)^b \qquad \frac{C_1}{C_2} = \left(\frac{e_2}{e_1}\right)^h = \left(\frac{V_1}{V_2}\right)^k$$

$$\frac{W_1}{W_2} = \left(\frac{V_1}{V_2}\right)^n \quad \frac{V_1}{V_2} = \left(\frac{I_1}{I_2}\right)^x \quad \frac{R_1}{R_2} = \left(\frac{V_1}{V_2}\right)^q$$

Exponent.	a	b	h	k	n	x	q
Tungsten.	3.80	6.65	1.75	3.68	1.59	1.718	0.418
Tantalum.	†*3.73	†*6.30	1.69	4.20	1.72	1.382	0.276
Gem.	*3.7	*5.8	1.6	4.9	1.8	1.25	0.20
Treated carbon.	3.65	5.83	1.59	5.55	2.07	0.930	-0.075
Untreated carbon.	*3.62	*5.43	1.50	6.89	2.31	0.763	-0.310

(*) Computed from the dotted curve of Fig. 12.
(†) Direct current.

The values given for h, k, n, x, and q are correct within the limits of accuracy of photometers and electrical instruments, therefore are correct within 1 per cent. The values of a and b, however are subject to much greater error, probably at least 5 per cent.

In applying correction figures to forced tests, we have found the exponent b to be the most convenient one to use, hence we call this the *fundamental* life exponent. The exponents k and x are also *fundamental* exponents, k being determined from photometric relations, and x from electrical relations. Given these three fundamental exponents, it is possible to determine the relation between *any* two of the variables, life, candle-power, watts, watts per candle, volts, current and resistance.

A curve plotted between x and k brings out some interesting considerations. As shown in Fig. 12, the points for all the lamps, except the gem fall on a very smooth curve. This is rather surprising, in view of the fact that the metal filaments exhibit more selective radiation than those made from carbon. The point shown in Fig. 12 for "old treated carbon" was obtained from performance curves of some treated carbon lamps which had burned for several thousand hours. The effect of this burning was to evaporate part of the graphitic layer deposited on the filaments in the treating process, or to partially "untreat" them. As could be anticipated, the point representing these lamps falls between those for treated and untreated lamps.

By using the curve of Fig. 12 it is possible to determine the relation between any two of the variables, but the life (excepting for lamps of the gem class) when either of the fundamental exponents, k and x, is known. The exponent x of the voltage-current equation is obviously the easier of these two to determine, as it can be obtained from voltage and current measurements of a lamp.

It is within the range of possibilities that future experiments may give a smooth curve between x and one of the life exponents.

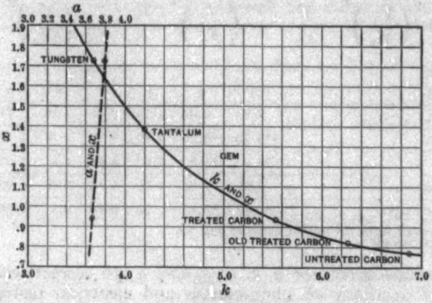

FIG. 12

If such proves to be the case, it will be possible to predetermine the *entire* performance of a lamp from its volt-ampere curve. The dotted curve of Fig. 12 is plotted between a and x. As only two points on this curve are known, it is drawn in as a straight line. Future developments may show that it has a slight curvature, but in the meantime it will serve as a good basis for calculations.

A paper presented at the 249th meeting of the American Institute of Electrical Engineers, New York, May 17, 1910.

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DUCTILE TUNGSTEN

BY W. D. COOLIDGE

When work was first started on the problem of producing a ductile form of tungsten, the metal looked very uncompromising. It was so hard that it could not be filed without detriment to the file, and was, at ordinary temperatures, very brittle.

It was of course known from the start that, at the operating temperature of a tungsten lamp, the metal was soft; but this fact seemed unavailing, for there was no tool that could be used for working the metal at such temperatures, and materials from which such tools could be made were lacking.

To a man ignorant of our success, the problem would certainly look more hopeless to-day than it did then. For since that time millions of tungsten filaments have been produced from all available tungsten ores, by widely differing methods, and by different groups of men. And each manufacturer has been fully alive to the fact that he must strive for the highest attainable purity. Yet all of the filaments made have been brittle. They are elastic and flexible as spun glass, but, like the latter, are incapable of taking the slightest permanent set.

Not only was there nothing in the past history of tungsten to encourage us, but, in the natural periodic system of the elements, the metal belonged to a family no member of which had been brought into a ductile state. The other members of the family are chromium, molybdenum, and uranium, elements which had always been characterized by hardness and brittleness. A study of the periodic system shows that, in a general way, elements of the same family do resemble one another in point of ductility, as well as in their other physical and chemical properties. For example, copper, silver, and gold are all in one family and are all very ductile.

Little encouragement could be drawn from the achievement of Dr. Von Bolton with tantalum, because of the fact that this element is in a different family. And the two families differ markedly in both physical and chemical characteristics.

The only arguments on which we could base the hope that tungsten could be produced in a ductile state, were founded on the effect of mechanical working and of chemical purity on the ductility of some of the other unrelated elements. But even this hope seemed of doubtful fulfilment, owing to the apparently insuperable difficulties of mechanically working this particular material.

Mechanical working increases the ductility of some metals. Cast zinc, for example, undergoes a marked increase in ductility when subjected to ordinary wire drawing processes. Some special steels, also, which, as cast, are coarsely crystalline, have to be handled very carefully until they have undergone a certain amount of mechanical reduction, while from this point on they are very ductile.

Chemical purity also, is, in general, conducive to ductility and in some instances, slight amounts of impurity produce a marked effect. Some striking examples of this are the following:

Copper is very sensitive to the presence of bismuth, even 0.02 per cent of the latter rendering it brittle when hot, and 0.05 per cent brittle when cold. Sulphur is also a harmful impurity, and copper containing 0.25 per cent of it is only moderately malleable.

Gold is rendered brittle by 0.05 per cent of lead, bismuth, or tin, and is no longer malleable when it contains as little as 0.0003 per cent of antimony.

Nickel is rendered unsuitable for rolling by the presence of 0.1 per cent of either arsenic or sulphur.

Platinum is made hard and brittle by 0.03 per cent of silicon. Its ductility is also considerably lessened by the presence of small quantities of the other platinum metals.

Tin is brittle when cast at a temperature either too high or too low.

The analogy with iron is in some ways more interesting than the above, for both tungsten and iron take up carbon, and may be greatly hardened thereby. And iron is extremely sensitive to traces of sulphur, phosphorus, and arsenic.

Our early experiments in mechanically working tungsten led to work on tungsten alloys, and on suspensions of tungsten powder in metals in which there was little or no alloying. One of the most interesting suspending media proved to be an alloy of cadmium, bismuth, and mercury. This amalgam is very pliable. For our purpose it has several other important characteristics. Upon heating to about 140 deg. cent., it becomes soft and plastic, and from this point it retains its plasticity over a considerable temperature interval. While the amalgam is in this state, it is possible to incorporate with it considerable quantities of many foreign substances, such as tungsten, in powdered form. (Such a mixture, containing about 30 per cent by weight of tungsten was exhibited at the meeting.) At room temperature, it is about as hard as lead, but, at a temperature of about 110 deg. cent., it can be readily pressed through a diamond die, and comes out as a silvery looking strong pliable wire. If this wire could be freed from everything but tungsten and still preserve its present strength and ductility, it would solve the tungsten filament problem. But such is not the case. Upon heating it by the passage of current, in a non-oxidizing atmosphere, the mercury first distils out then the cadmium and then the bismuth. Some shrinkage takes place as the foreign metals leave the filament, and the remainder is brought about by raising the temperature to white heat. Most of the ductility of the wire leaves with the mercury, and the remainder goes with the cadmium. This finished filament has been used in thousands of lamps, but these all lack ductility.

The above experience was duplicated when we tried copper as a binding agent for the tungsten, and again when nickel was used for this purpose. In each case there was a ductile stage in which the filament could be bent and otherwise manipulated, but not a trace of this ductility remained after the removal of the foreign element.

The above experiments gave us several new and valuable methods for producing tungsten filaments of the usual quality. But in so far as our ultimate goal, a ductile tungsten filament, was concerned, they were not promising. They were, however, in one respect, instructive, for in the case of all of the above and with many other foreign additions, we got a complete removal of the foreign elements, at least so far as our analytical tests showed, with the final high temperature treatment of the filament. This seemed to indicate that we either did not need to worry about contamination from such elements, or else that brittleness was due to traces of impurity so minute as to escape detection by our analytical methods.

To return now to the mechanical working of pure tungsten. This work received a great impetus by our discovery that an ordinary, dense, well sintered, tungsten filament can be easily bent and put into various forms, and otherwise manipulated at temperatures well below redness, and even below the temperature at which appreciable oxidation takes place. This helped us in two ways. First, it reduced the temperature at which mechanical working operations could be carried on, and, second, it gave a means of recognizing which of the mechanical and chemical processes involved in our experiments were bringing us nearer to the goal. Anything which reduced the temperature at which the metal could be permanently bent was, clearly, helping us.

We found that steps tending to the elimination of the last traces of certain impurities did greatly improve the resulting product. While it may be true that certain impurities present in small amount are harmless or even helpful, we know that certain other impurities are detrimental. We also found that a certain micrographic structure in the tungsten rod with which we start, was conducive to mechanical working and to ductility in the resulting product. Once arrived at the point where mechanical working was easy and where there was a certain amount of ductility in the product even when cold, the development became more rapid. It was aided by the construction of more refined apparatus, in the design of which care was taken to guard against the taking up of impurities during mechanical reduction processes, both from the atmosphere in which the work is carried on and from the surfaces of the tools.

Hand in hand with this improvement on the mechanical side has gone the work on greater chemical purity of the metal with which we start. One of the difficulties in purifying tungsten has been due to the fact, which has been pointed out by Smith and Exner and others, that tungstic acid is very prone to form difficultly separable complexes. Because of this tendency, especial care must be taken with regard to the purity of the reagents used, as otherwise recrystallization beyond a certain point does not result in corresponding purification.

The knowledge obtained from our various lines of research now makes it possible for us to prepare tungsten which can be mechanically worked without more difficulty than would naturally attend the manipulation of very fine wire.

The product which we now have is a perfectly pliable ductile wire, which has the strength of steel. (Specimens of ductile tungsten wire of various sizes were exhibited at the meeting.) It gives a lamp which is strong and whose filament retains its ductility throughout the life of the lamp.

The following data on the drawn wire, obtained from measurements made in the laboratory by Dr. Colin G. Fink, may be of interest:

Diameter (in inches)	Tensile strength (lb. per sq. in)	Specific gravity
0.150	—	19.30
0.005	490,000	—
0.0028	530,000	—
0.0015	600,000	20.19

The electrical resistivity at 25 deg. cent., expressed in microhms per centimeter cube, is, for the hard drawn wire, 6.2, and for the same annealed, 5.0.

The temperature coefficient of electrical resistivity between 0 deg. and 170 deg. cent is 0.0051 per degree centigrade.

The above values, with the possible exception of the temperature coefficient, are of course somewhat dependent on the early history of the wire from which they were determined.

The work which has been outlined above is the result of the close coöperation of about 20 trained research chemists, with a large body of assistants, in the research laboratory. These men were of course given, from the factory organization, all of the mechanical and electrical assistance they could use, and were assisted in no small measure by the staff of the incandescent lamp factory.

A paper presented at the 250th meeting of the American Institute of Electrical Engineers, New York, May 27, 1910.

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THE APPLICATION OF PORCELAIN TO STRAIN INSULATORS

BY W. H. KEMPTON

Porcelain possesses some qualities which make it a very good material for line insulators and especially strain insulators. It can be moulded and worked into almost any desired form or size; when made of proper materials and properly burned it has practically no depreciation when exposed to the weather, acid fumes or gases, which sometimes create so much havoc on electric lines. It is hard and dense and has high dielectric strength. It is practically non-absorbent and so is not affected by frost.

The great difficulty in the use of porcelain is its lack of elasticity. It is practically inelastic and has low bending and tensile strength. It has fair shearing strength and good crushing strength. It is these last two properties that make it available for strain insulators.

In order to have definite working data, tests were made to determine the strength of what is known as high voltage stock, in compression, shear and tension. After a number of trials, a pony insulator of the dimensions shown in Fig. 1, and a transposition insulator, Fig. 2, were selected for the compression test. These samples were placed in a Riehle tension and compression machine having a piece of ⅜-in. fibre above and below the samples to take up irregularities in the porcelain. In the case of the pony insulator, Fig. 1, the break always occurred at the upper groove, and at the middle groove of the transposition insulator, Fig. 2. The average breaking stress for the insulator shown in Fig. 1 was 16,370 lb. per sq. in.; high 21,400 lb., and low 12,200 lb. For the one shown in Fig. 2 the average breaking strength was 12,690 lb. per sq. in.; high 17,400 lb., and low 8,200 lb. In each case the results are from 10 samples. The shape and proportions of the insulators doubtless account for the different results in the two cases.

For the shearing test, ten pieces like that shown in Fig. 3 were tested in the manner described above. The fracture in each case showed almost pure shear on the line indicated in the sketch. The average shearing stress was 2400 lb. per sq. in.; high, 2,880 lb., low 1,770 lb.

For determining the tensile strength of porcelain, a number of porcelains from insulators like the one shown in Fig. 9 were selected. They were supported by a free but close fitting ring about the projecting head, and load was applied by means of a steel pin resting against the bottom of the pin hole. Only figures from samples showing a pure tensile break were used in the calculation. The average of nine samples was 654 lb. per sq. in.; high 897 lb., low 539 lb.

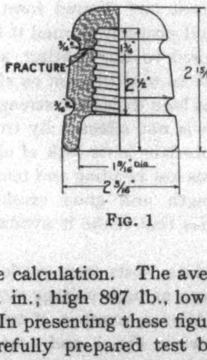

FIG. 1

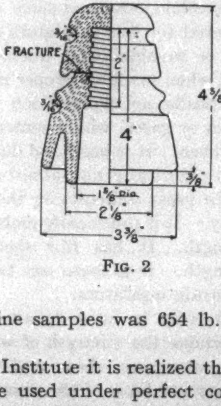

FIG. 2

In presenting these figures to the Institute it is realized that if carefully prepared test blocks were used under perfect conditions, much higher results would be obtained, showing the porcelain to better advantage. If the object were an investigation of the porcelain stock such results would be preferable. However, the object of these tests was to secure data for use in insulator design. Inasmuch as perfect conditions cannot be obtained in the practical manufacture of insulators, it was thought that tests from stock insulators under conditions including the imperfections met with in design and manufacture would be more reliable than absolute data obtained from perfect test blocks under ideal conditions.

SOME FEATURES IN THE DESIGN OF PORCELAIN STRAIN INSULATORS

As porcelain is strongest in compression, the preferable form of a strain insulator from the standpoint of mechanical strength would be one in which only compression strains existed, and in which sufficient stock was placed under the load to give a proper factor of safety. In practical design this condition is difficult to realize, and the load on most types of insulators gives a combination of compression and shearing stresses.

There are three types of porcelain strain insulators, suitable for high voltage railway work, now on the market and in successful service. The spool type, the loop type, and the compression or barrel type.

The spool and the loop types are the simplest and oldest but both are limited in mechanical strength owing to the fact that the load is applied between a cable and pin at right angles, and two cables at right angles, respectively. This throws a comparatively small volume of porcelain in direct compression, the larger part of the load producing bending stresses.

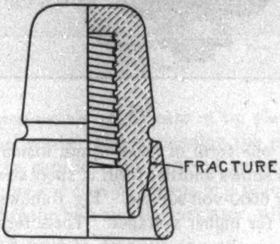

FIG. 3

The spool type insulator is further limited mechanically by the possible bending strength of the pin, and electrically, by the amount of surface insulation possible. On account of the inelasticity of the porcelain, if the pin fits the hole in the insulator snugly and the hole is of uniform diameter, the least bending of the pin will throw a bending stress on the insulator and break it. If a metal sleeve be cemented in the pin hole to distribute the load along its length, the expansion of the metal with heat may burst the porcelain. Practical design has settled down to a form of pin hole smallest in diameter under the wire groove and enlarging toward each end. This allows the pin to bend without pressing on the ends of the pin hole. The problem then becomes one of designing a pin of such length as to allow the desired insulation, and of such diameter as to give the desired bending strength. Of course the walls of the porcelain must be made sufficiently thick to also stand the load.

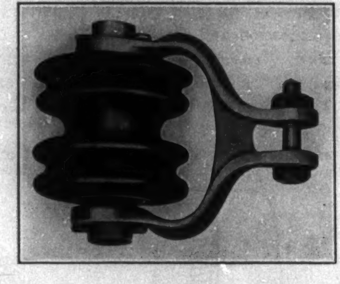

FIG. 4

Fig. 4 shows one form of spool strain insulator for 1200-volt service. Fig. 5 shows another form of spool strain insulator with a shorter pin for 6600-volt service. Fig. 6 shows a form of spool strain insulator for higher voltages. These forms of spool strain insulators have an ultimate strength of from 9,000 to 12,000 lb.

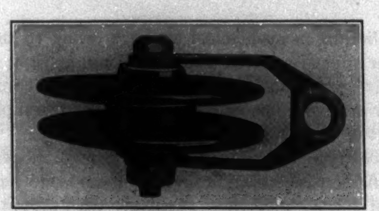

FIG. 5

The ideal porcelain strain insulator would have the load-bearing portion of the porcelain made with two exactly parallel surfaces held between two exactly parallel and absolutely rigid plates. Fig. 7 shows a form of compression insulator which approaches this condition. It consists of a porcelain bushing with an undercut head portion so that two approximately parallel bearing surfaces are obtained. The head of the bolt passing through the bushing rests on a steel washer bearing on its inner end, and the shoulder of the bushing rests against an inner end of a split cylindrical case, riveted or bolted together over the porcelain head. The irregularities incident to the practical manufacture of porcelain are taken care of by placing a lead washer under the steel washer and embedding the portion of the insulator inside the case in neat Portland cement. The bolt head is insulated from the case by means of a porcelain cap cemented over the head of the bolt and the insulator, with a good insulating cement.

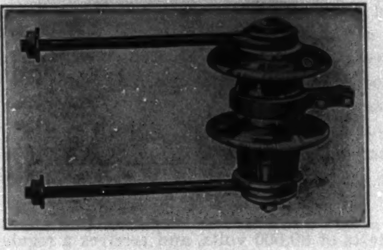

FIG. 6

The chief requirement in the design of this form of insulator is to make the case of such form, and to reinforce it with ribs, so as to prevent the end bearing surfaces from sagging. If these surfaces sag it throws the load on the outer rim of the porcelain head causing the sides to split off. One sample with a 4-in. diameter head stood a test of 34,000 lb., at which point the bolt broke. On tearing down the insulator a crack in the porcelain was discovered with difficulty. Insulators of about half the

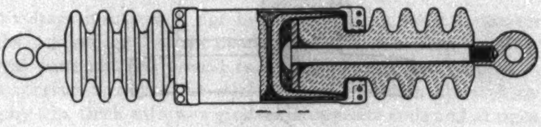

FIG. 7

above size, with 2½-in. diameter heads, will stand mechanical tests of from 18,000 to 20,000 lb.

The size mentioned as standing a 34,000-lb. stress—5½-in. diameter of corrugations by 24 in. long—has stood break-down electrical tests of 80,000 volts, and receives a regular shop test of 50,000 volts for one minute.

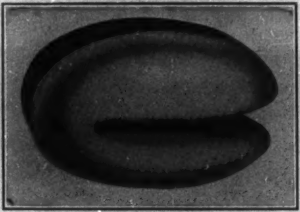

FIG. 8

It was thought that high mechanical stresses weakened the porcelain stock electrically. To determine this point the following tests were made. Twenty-six insulators like that shown in Fig. 9 were connected in series for simultaneous mechanical and electrical tests. The load was increased by small steps, 70,000 volts being placed on each insulator for 15 seconds at

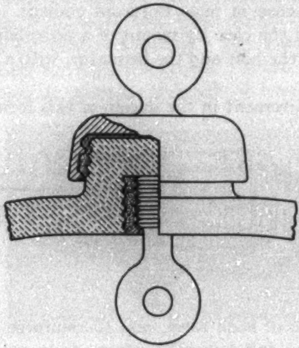

FIG. 9

each step. The test was carried on until three insulators had broken, the broken insulators being replaced each time, and in no case did the porcelain puncture before mechanical breakdown. The failure always resulted in breaking the porcelain off at the lower edge of the cap, so that each porcelain was tested at 70,000 volts at practically its ultimate mechanical strength.

A second test consisted of connecting ten loop strain insulators in series and applying the same test as before. In this case three of the insulators punctured before any of them broke. Inasmuch as this happened at the normal breaking load of the samples and as seven of the ten did not puncture it was thought probable that the high stress in the section of porcelain under the load opened up slight flaws in the stock rather than causing the sound porcelain to puncture below its unstrained puncture voltage.

It will be noted that the above discussion on design is all on high-voltage insulators. For low-voltage work what is known as the " goose egg " strain insulator, Fig. 8, has been used for several years and has proved to be quite strong and reliable.

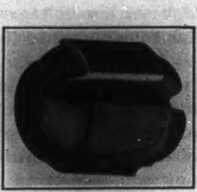

FIG. 10

It consists merely of an oval mass of porcelain about 5 in. long by 3 in. thick with wire grooves in opposite ends and at right angles to each other. Practically all of the porcelain helps carry the load directly or indirectly, and a very strong insulator results. Its proportions also make it quite sturdy and proof against rough handling. The ultimate mechanical strength is from 12,000 to 14,500 lb. A smaller size 3½ in. long, shown in Fig. 10, stands from 9000 to 12000 lb. stress.

These results are from tests made with ½-in. high-grade seven-strand steel cable. If a more flexible cable had been used, higher results would have been obtained, as the hard strands of the cable used tended to cut into the insulator, and being so stiff, did not conform closely to the grooves.

On account of the rough usage they are apt to receive in low-voltage work, however, the moulded form of strain insulator has been more popular. The load being carried directly by metal parts with hard and tough insulation, usually sheet mica, interposed between and surrounded by tough moulded protecting covering, makes a very reliable insulator mechanically, and one that, on low-voltage work, is reliable electrically.

For high-voltage work moulded strain insulators are not so well suited. To stand the higher electrical test the metal parts must be further apart. On account of the resulting greater leverage, to maintain the same mechanical strength, the metal parts must be made much heavier. When large iron parts are embedded in the moulded insulation the expansion and contraction of the metal with heat is apt to crack the covering and admit moisture.

As compared to porcelain all forms of moulded strain insulators whether for high- or low-voltage work possess the element of depreciation due to exposure to the weather that porcelain does not have.

Wood strain insulators for both low- and high-voltage work have become quite popular, chiefly for the reason that long service tests have proved them to be reliable. Owing to the general unreliability of wood, the manufacturer must exercise much care in purchasing and inspecting his stock to maintain its quality. Equal care must be exercised in inspecting the metal caps before and after swaging them to the sticks. Even then, defects are apt to escape the inspector, and it is desirable to test every wood strain insulator mechanically before shipment, to make sure of results.

It will be noted that, although the porcelain strain insulator has certain inherent weaknesses, so has every other kind, and a perfect material for this purpose remains to be discovered.

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ELECTRIC RAILWAY CATENARY TROLLEY CONSTRUCTION

BY W. N. SMITH

During the past twenty years overhead trolley construction for electric railways has become such a familiar type of engineering construction, and apparently so settled in practically all its detail, that it is apt to be regarded as commonplace compared with many other features of electric railway equipment engineering. As long as the electric energy for train propulsion was everywhere standardized at 500 to 600 volts direct current, trolley construction practice followed a comparatively well settled and practically uniform line of standards; but since 1904 wide departures have been made from the original forms of railway motors, both as to current and voltage. This advance, made entirely in the interest of economy in transmission, has been accompanied by radical changes in trolley construction which have required the closest engineering attention and have lifted it above the level of the commonplace into which it had generally come to be relegated.

This paper is intended to be a review of current practice in electric railway catenary construction, its purpose being to bring some details of the present state of the art before the Institute in a practical way, to call particular attention to such features of it as may seem to be open for discussion, and to invite expressions of opinion about them; and it is hoped that each interested member will contribute something from his own practical experience so that an interchange of ideas will result which will be helpful to all concerned.

It may be well to state at the outset one cardinal point about overhead trolley construction, which is often overlooked by those who have given their time chiefly to the fascinating study of electric railway equipment predetermination and especial peculiarities of electric railway motors. I refer to the one thing which makes the electric railway differ from all other forms of electric power transmission and distribution, and that is the fact that the motor derives its power from a moving contact, maintained essentially parallel with the line of travel followed by the motor. The moving element of this contact is carried on the car or moving load, but the fixed element must be as long as the railway line itself, and every inch of it must at all times be in alignment and effectively insulated in order to make the entire railway system effectively useful. No matter how efficient the power station or the motors may be, neither is fully effective unless the contact wire through which they are joined is at practically 100 per cent efficiency. This efficiency must be continuously maintained over long distances and under all conditions of weather and of accidental or intentional interference; and the impossibility of relaying it without interrupting service makes the contact wire the most difficult and uncertain part of the entire system to maintain.

As interurban railways grew in importance, and in the size and speed of their equipment, not only did the necessity for economy in power transmission grow increasingly important, but the problem of collecting trolley current at high speed became more and more serious. The figure 8 and grooved types of trolley wire afforded some relief, but as supports were still 100 ft. or more apart the points of suspension caused slight changes in elevation of the wire, sharp enough to make trouble at high speed. It was not until 1904 that a new step was taken, namely, the elimination of the sag by means of more frequent points of support of the wire, resulting in the development of the so-called catenary type of suspension. This consists simply in suspending the trolley wire practically without sag by hangers of varying length placed every 10 ft., (sometimes 15 ft. or more) the same being supported by a messenger wire hanging in its natural catenary curve directly over the trolley wire. The messenger wire alone is supported on insulators. This type of construction was first successfully carried out on the Indianapolis & Cincinnati Railway, in 1904 from the designs of Mr. B. J. Jones.

This principle of construction has since been adopted in a number of other installations, with some modification, and has come to be accepted as a practical solution for high speed trolley operation. The original installation was made for 2,200 volts, and installations are now in service with this type of construction using voltages all the way from 600 to 11,000.

The principal features combined in this construction are the flat and smooth alignment of the trolley wire for high speed, the prevention of a trolley wire falling to the ground when broken, which is imperative with high potentials, and the use of a pneumatically-operated sliding bow for making contact, which dispenses with the trolley rope, avoids the necessity of frogs at switches and will stay on the wire at any speed regardless of the swaying of the car.

Although the above mentioned advantages of the sliding bow would seem to be conclusive for high tension trolley operation, it has the drawback of responding more sluggishly to unevenness of the trolley wire than the wheel and pole type of trolley, and this has resulted in a number of cases in the retention of the wheel trolley even in 3,300- and 6,600-volt lines. The writer's observation leads him to believe that the objections to the bow trolley have developed particularly where the catenary construction is defective, due to lack of appreciation of essential difficulties in construction and maintenance, and lack of skill in meeting them. It is easy to allow an amount of slack to go into a catenary trolley wire that will cause sufficient sag in the 10-ft. sections to make kinks at the hanger points, and under such circumstances high-speed operation with a sliding bow trolley is extremely unsatisfactory on account of the resulting sparking and flashing, while with a wheel trolley whose rate of vibration is about double that of the pantagraph, such a condition is not so prejudicial to smooth operation.

Types of Construction. Catenary construction is divided into three types as follows:

1. The original and most common is the plain single catenary, with the trolley wire hung directly from the messenger wire.

2. The compound or three-wire single catenary, in which the trolley wire is suspended by clips of uniform length from a tight secondary wire just above it, this secondary wire being supported by hanger rods of varying length from a slack messenger wire above it. There are several variations of this type and it permits the use of devices which maintain a uniform tension on the trolley wire through any range of temperature.

3. Double catenary construction, consisting of two messenger wires and one trolley, the latter below and between the other two, the three wires being at the corners of an equilateral triangle and rigidly connected by triangular pipe spreaders varying from 6 in. to 6 ft. on a side according to the sag of the messenger wire. The excessive rigidity of this type has been found to be undesirable in practical operation, and it has been successfully modified on the New Haven railroad by stringing a second trolley wire and fastening it a few inches below the first by clips at points halfway between the original trolley wire hangers. This construction was fully described and illustrated by Mr. W. S. Murray in his Institute paper of December, 1908.

The second of these general types has been extensively developed in Europe, particularly that feature which enables the maintenance of uniform tension on the trolley wire. Conspicuous examples of this type are the single phase lines of the Blankenese-Altona-Hamburg-Ohlsdorf line in Germany, and the Rotterdam-Haag-Scheveningen line in Holland.

Poles and Bridges. No paper on overhead construction can be regarded as complete without giving due consideration to the materials and construction of the poles or towers on which it is carried. In working up this division of the subject, however, there has been accumulated sufficient material of interest to warrant treating it in a separate paper, which the writer hopes to be able to do in the near future.

Where wooden poles are used they should invariably be treated with some preservative, preferably of the creosote type, before being set. The treatment may be either by the vacuum process which involves an expensive plant but thoroughly impregnates the wood; or it may be by the so-called " open-tank " process, in which about eight feet of the butts are treated with hot creosote or similar oil; or, cheapest of all, and yet quite effective, the " brush method " may be used, which simply means painting the pole with hot creosote or similar oil for a distance of about two feet above and two feet below the ground line, applying a second coat after the first coat has had time to soak in. Any engineer can prove to his own and to his client's satisfaction that either of the last two named methods of treatment will pay dividends, as the life of any pole so treated will be lengthened anywhere from 30 to 75 and possibly 100 per cent, according to the treatment used.

Steel poles can be had in three types. The familiar two- or three-section tubular pole, in either standard or extra heavy pipe; the "tripartite" pole, built up of re-rolled Bessemer steel U-sections with malleable iron collars and spreaders, the steel having an ultimate tensile strength of 100,000 lb. per sq. in.; and the "diamond" pole which consists of two sheet steel

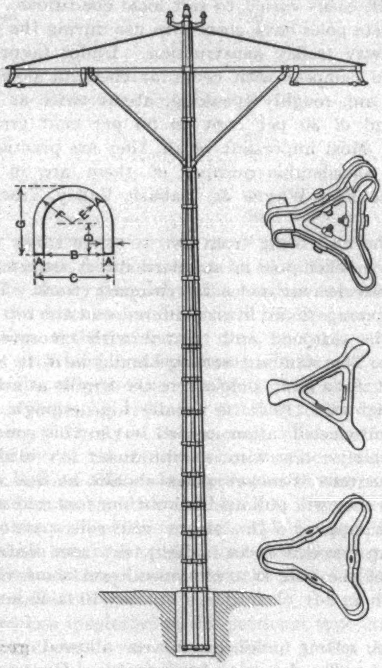

FIG. 1

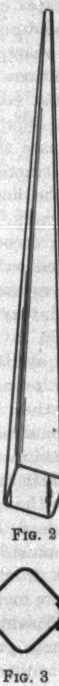

FIG. 2

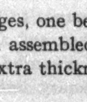

FIG. 3

"Tripartite" and "Diamond" steel poles

V-shaped troughs tapered and flanged over the edges, one being driven lengthwise within the other to form, when assembled, a box shaped pole, the extra strength lying in the extra thickness of the overlapping flanges.

The relative merits of these three types of steel poles may be briefly summed up by saying that the tubular type is the least economical of weight for a given strength; and that while the diamond pole is superior to the tripartite in the matter of weight economy, the tripartite has a great advantage in that the Bessemer steel composing it is almost rust-proof and that every inch of metal surface upon it can be reached with a paint-brush. Its taper can also be easily varied to suit local conditions.

Reinforced concrete poles have come into use during the past few years, for railway trolley construction. Under favorable conditions they can compete with cedar or chestnut poles as to first cost; they are, roughly speaking, about twice as stiff as a cedar pole and of 30 per cent to 50 per cent greater ultimate strength. Most important of all, they are practically indestructible. A considerable number of them are in use on the lines of the Fort Wayne & Wabash Valley Traction Company.

On account of the load being from two to three times that carried on a single bracket pole in standard direct suspension, it is necessary to use heavier poles for catenary work. If of wood, they should average 25 in. in circumference at the top and should invariably be seasoned and treated with creosote, at least at the butts. The standard setting should be 6 ft. for a 30-ft. pole and 6½ ft. for a 35-ft. pole where the wire is at a high elevation. Over highways, 19 ft. is usually high enough, but in the steam railroad electrification carried out in this country the standard height of trolley wire, except under low bridges, is 22 ft. above the rail. Bracket poles should be set with 14 or 15 in. rake, as they will pull up to about one foot rake after the load has been applied. On steam railroads particular care must be paid to side clearances. Eight feet from center of track to the face of the pole is a minimum, and some roads require more. With an 8-ft. clearance, a bracket 10 ft. in length is sufficient.

Early practice in setting poles on curves, allowed greater offsets than experience has shown to be desirable. One manufacturer's catalogue gives pole spacing based on a maximum variation of 17 inches in the position of the trolley wire with reference to the center of the track. Another one gives seven inches, and a third is somewhere between. It is much safer to prescribe small offsets, and the Denver & Interurban catenary line was laid out not to exceed 3½-in. offsets, as follows:

TABLE OF POLE SPACING ON CURVES

Degree of curvature	Pole spacing feet	Max. offset of trolley wire from center of track, inches
Tangent	120	0
1	120	1.87
2	110	3.37
3	90	3.06
4	80	3.37
5	70	3.06
6	60	2.87
7	50	2.34
8	50	2.64
9	50	2.94
10	50	3.24

On curves, brackets must be so inclined from the horizontal as to be nearly parallel to the position taken by the pantagraph bow, the outer end of which will tilt up considerably, due to the elevation of the outer rail.

For attaching bracket truss rods to pole tops, the three-part pole-collar (Fig. 8) is preferable to any other means, as a single pattern forging is sufficient not only for the truss rod but for constraining the body of the bracket. This method was devised by the writer for the bracket construction of the Denver & Interurban R.R. in 1907. Insulator pins should be tightly adjustable on the brackets and should be made with a two-part clamp base, which the writer believes preferable to one with a J-bolt base as the J-bolt base will open out when screwed up tightly and has a very limited area of contact on the inside. Insulator pins should be of malleable iron.

Porcelain insulators of the petticoat type, are now universally used, and even over steam railroad tracks they have given no special trouble from gathering soot. The types used on the Erie and the Denver & Interurban lines have been uniformly successful, for three years on the former and two years on the latter railroad. The general form of this insulator is shown in Fig. 4.

Brackets ought also to be stronger than are usually made in direct suspension, particularly if over steam railroads. In the equipment designed by the writer for catenary construction on the Erie Railroad, two truss rods were used per bracket.

Some forms of bracket are made with two horizontal members, one on each side of the pole. To guard against accidents and minimize breakage in case of accident, the writer believes that it is desirable to design the pole attachments to the bracket so that if the trolley and messenger wire break, the bracket and truss rods may be swung around the pole as on a hinge, rather than be broken off or twisted out of shape. This is effected by using pole collars at the butt of the bracket and at the point of attachment of the truss rod, offering the additional advantage of obviating the boring of holes through the pole. Figs. 5 to 10 show several types of brackets used experimentally by the Connecticut Company. For high voltages, the brackets must be grounded to the rail to prevent a broken insulator from causing the pole to be set on fire.

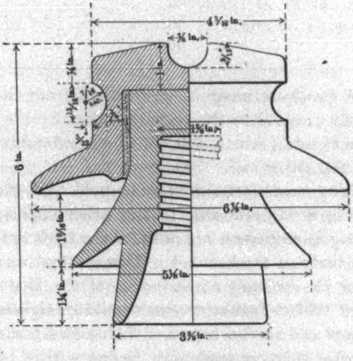

Fig. 4—Porcelain insulator

Catenary Spans and Bridges. The expense of steel bridges for supporting catenary trolley wires over more than two or three adjacent tracks can be greatly reduced by using span wire construction. A number of spans constructed under the writer's supervision at the Rochester terminal of the Erie railroad are illustrated herewith in Fig. 11. In this design the span wires and all supporting fittings are grounded. The trolley wire is supported by suspending from the span wire a stirrup of the same size of tee iron as is used for the bracket. The same type of pin as well as insulator is used for the span as for the bracket construction on the remainder of the line. The voltage on this installation is 11,000. For lower voltages heavy wooden strain insulators are sometimes cut into the spans without any insulation between the span and the messenger wire at the point of attachment, but the advantage of entirely grounded span wires should commend itself so obviously that it does not seem worth while to go to the extra trouble of working various styles of insulators into them.

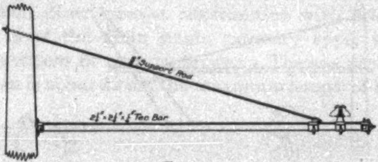
Support Rod
2½" × 2½" × ¼" Tee Bar

FIG. 5

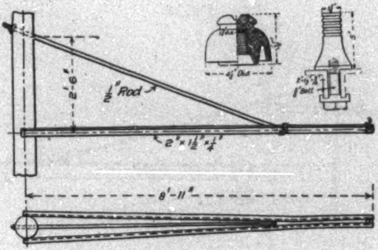
2'-6"
½" Rod
2" × 1½" × ¼"
4½" Dia
5"
8'-11"

FIG. 6

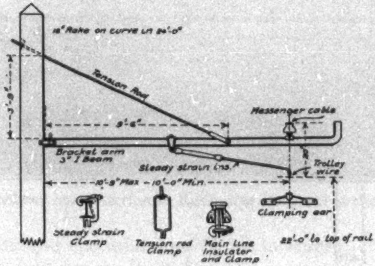
18" Rake on curve in 84'-0"
Tension Rod
3'-9"
9'-6"
Messenger cable
Bracket arm
3" I Beam
Steady strain ins.
Trolley wire
10'-9" Max - 10'-0" Min.
Clamping ear
Steady strain Clamp
Tension rod Clamp
Main line Insulator and Clamp
22'-0" to top of rail

FIG. 7

This form of span is practically in duplicate, though it is intended that the upper should carry the load and the lower act to steady the stirrup sideways. It is hardly necessary to add that steel poles are necessary for catenary span construction of this character, unless there is ample room to substantially guy wooden poles. For this purpose the tripartite pole has been found very satisfactory. The illustration shows seven tracks spanned, being a distance of 96½ ft. across the tracks between poles, and four tracks of the seven electrified.

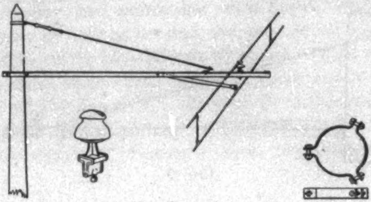

FIG. 8

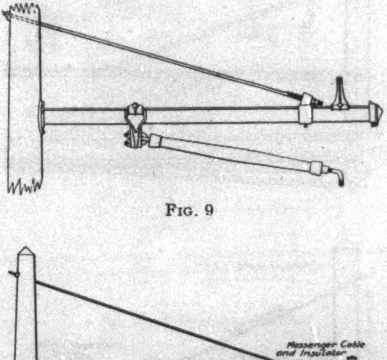

FIG. 9

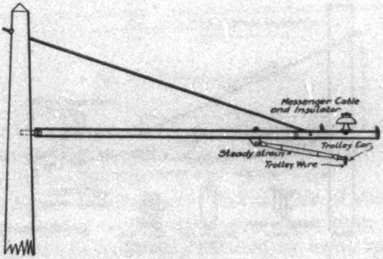
Messenger Cable
and Insulator
Trolley Ear
Steady strain
Trolley Wire

FIG. 10

Some of the latest catenary construction for double track has been supported by a light bridge construction, the most recent example being that of the Rochester, Syracuse & Eastern Railway, recently completed, and illustrated in Fig. 12. This is for 600-volt direct-current construction with bridges 300 ft. apart. It is of the plain single catenary type, without any special adjustment or tension devices. The sag of the cables in a 300 ft. span is about 62 in., the maximum length of hanger being about 67½ in. and the minimum 5¼ in. in length. The form of bridge and foundation is stable and permanent. The side frames of the bridge are 28 ft. between the centers and the spread of each base is 4 ft. The insulators on top of these bridges are of porcelain moulded in a special saddle shape and set on treated timber. There is said to be comparatively little side swaying between bridges. On this particular line the messenger cables are of copper, constituting the feeders and are of 500,000 cir.

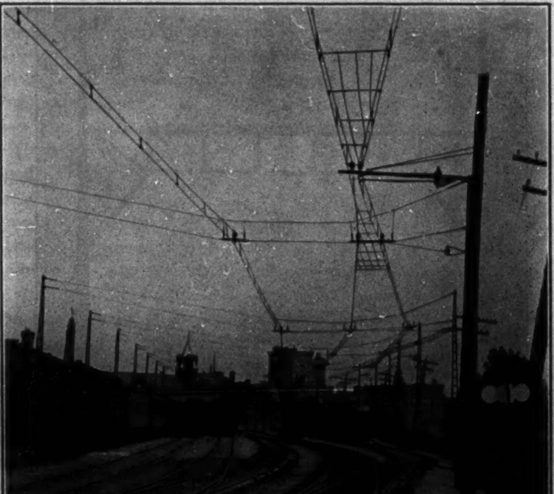

FIG. 11—Overhead construction at Rochester terminal of the Erie railroad

mils. The feeder was necessary for power distribution and the cost of the steel messenger wire was saved by this combination.

In the *Electric Railway Journal* for May 22, 1909, were published some figures showing the relative cost of this type of construction compared with the ordinary wooden pole and span wire construction for double track. The fact that the messenger wires were eliminated and the feeders made to do double duty enabled quite a saving to be made, and the cost of the supporting structures, exclusive of copper conductors, is reported for this particular line as being only $100 per mile of double track more than with wooden pole construction. It is hardly necessary to comment on the greater permanency of steel construction.

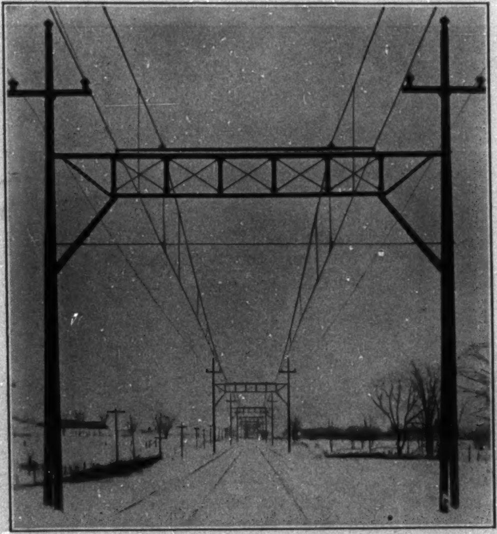

FIG. 12—Light bridge construction on Rochester, Syracuse & Eastern railway

The varying costs of steel bridges, poles and wires render it necessary to make very careful estimates for comparison before the engineer commits himself to the adoption of a radically new type of construction, but there will doubtless be many instances where this type of bridge for a double-track line would prove economical.

The original bridge construction of the New Haven Railroad has been so frequently described and illustrated that it is only necessary to refer to it by name. The newer type of construction now being used by the New Haven Railroad will be referred to later. The writer believes it to be a great improvement over the original.

Messenger and Trolley Wires. By reason of their somewhat intimate relationship, it is desirable to consider messenger and trolley wires together. The original and simplest form of catenary construction utilized a galvanized 7-strand steel cable of high strength steel, with hard-drawn grooved copper trolley wire. The messenger wire has varying sags but a common sag was 10 to 12 in. for a 120-ft. span. The trolley wire which is generally of 3/0 or 4/0 B. & S. gauge, is meant to be perfectly level at average temperature, but owing to the different coefficients of expansion of steel and copper, the trolley wire is relatively tighter at low and slacker at high temperatures than the messenger wire. With the plain type of catenary construction where no take-up devices are employed, the result is that in warm weather the 10-ft. sections between hanger points become slack enough to cause the sliding bows to pound kinks into the wires at the hanger points, and, at any considerable speed, mechanical pounding and electrical flashing are both injurious. The only remedy for this situation aside from providing overlapping breaks, is to pull the wire so tight that its strain at maximum temperature will not be less for a 4/0 copper wire, than 2,000 lb. If the minimum tension at 100 deg. fahr. is to be 2,000 lb., at zero deg. fahr. it will run up to about 5,000 lb., and the elastic limit of the wire is reached at 5,817 lb. As 5,000 lb. is so close to the elastic limit it is to be expected that copper trolley wire pulled tight enough to be effective at maximum temperatures will be likely to get pulled beyond the elastic limit in the course of a season or two, particularly after the outer skin is somewhat worn down by the passage of the moving contact. These considerations may explain much of the trouble that has been experienced with plain catenary construction using hard drawn copper trolley wire. It sometimes happens that when a road is quite crooked, the elasticity of the poles will do something towards maintaining the tension of the trolley wire at varying temperatures by giving sideways at the curves, but usually the only remedy is to pull out the slack as often as required.

This warm-weather slackness can be obviated where a wire can be pulled sufficiently tight to be at a minimum of 2,000 lb. at a high temperature and 5,000 lb. at low temperature. This can be done with "phono-electric," with steel wire, or copper-clad steel wire. The principal objection to the use of wire other than copper is the decreased conductivity. Phono-electric wire costs more than copper, while steel wire, of course, costs very much less. Both of these wires are so much stiffer than hard drawn copper that there is a marked tendency to resist kinking. At 11;000 volts the conductivity does not greatly matter when dealing with the usual interurban train weights and distances of transmission.

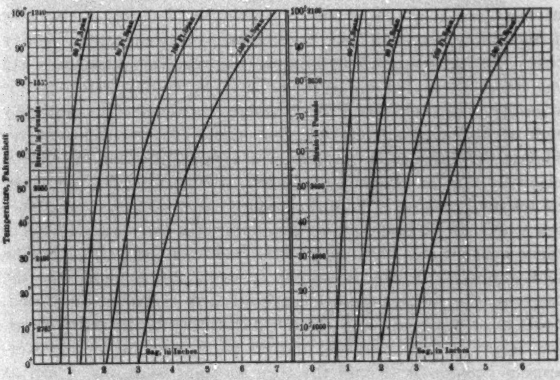

FIG. 13—Curves of messenger and trolley sag

On the Denver & Interurban Ry. in 1908, phono-electric trolley wire was strung on 45 miles of plain catenary construction, using a dynamometer to register the tension, which was so adjusted that at 100 deg. fahr. there was not to be less than 2000 lb. tension, rising to nearly 5000 lb. at zero deg. fahr. The curves of messenger and trolley sags are shown in Fig. 13*. The road has been in constant operation for two years and it has not been necessary to pull any slack out of the trolley wire in that time, thus demonstrating the correctness of both the design and the selection of materials.

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* From a paper on "Catenary Trolley Construction" read before the Am. Soc. C. E., October, 1908, by O. S. Lyford, Jr.

The use of tension devices for trolley wire as thus far developed, which is chiefly in Europe, does not seem to contemplate tensions of more than 1000 to 1500 lb., and furthermore the clips which hang the trolley wire from the secondary wire directly over it are of a type that will yield vertically, so that the trolley can, as it were, carry a wave along with it as it travels underneath the wire. It is the writer's belief that without the upwardly yielding hangers, it is necessary to maintain a minimum tension of at least 2000 pounds; and that it is permissible to maintain a lower tension only when the trolley wire can yield upwardly at the hangers. Such hangers have not yet been generally adopted for use in this country and the only experiments with them under American conditions of which the writer has knowledge, have not been particularly conclusive. On the New Haven road good results have been effected by a maximum tension of about 5000 lb. on the trolley wire, and without the use of automatic devices for producing uniform tension under all temperatures.

A table is presented herewith showing the characteristics of the four kinds of wire now available for catenary construction, those characteristics being for one size only, No. 4/0 B. & S. gauge, which is that most largely used in catenary construction

PROPERTIES OF TROLLEY WIRE, NO. 4/0 B. & S. GAUGE

	H. D. copper	Phono-electric	Copper clad	Steel
Tensile strength, lb.	8,310	11,330	9,470	12,000
Elastic limit, lb.	5,817	9,640	8,523	9,000
Res. per mile, ohms	0.259	0.575	0.634	2.21
Weight per mile, lb.	3,382	3,382	3,140	2,940
Modulus of elasticity	16,000,000	18,500,000	—	30,000,000
Coeff. of expansion, deg. fahr.	0.00000950	0.00000932	—	0.00000640

An excellent feature of the modified type of compound catenary construction used by the New Haven R.R. is the upward yielding made possible by suspending the contact wire from the old trolley wire at points halfway between the original hanger points. There is thus available a limited amount of upward yielding, depending somewhat on the temperature. The combination of this yielding effect with the high tension in the contact wire has proved so generally satisfactory that in future extensions of the New Haven system the contact wire is to be similarly suspended. The clips by which the working conductor is attached to the lower or secondary messenger are fast to both the wires and allow no vertical play other than that due to the yielding of the secondary wire.

The European compound catenary however has these hanger clips so designed as to permit the trolley wire to yield vertically and as all new European work seems to be designed along these lines the principle under European conditions seems to be successful.

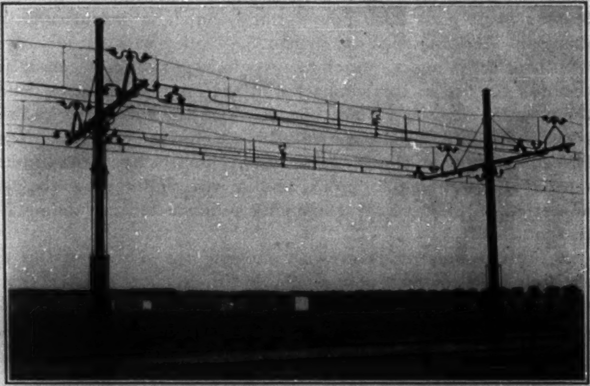

FIG. 14—Catenary construction with strain insulator at each bracket

The other principal feature of the compound catenary is the tension device placed at intervals to take up the expansion in the trolley wire due to temperature. This consists of a system of weights operating by chains over pulleys, pulling against the free end of the trolley wire at the end of each section, the consecutive sections overlapping so that the contact bow slides readily to one before leaving the other, there being, however, no electrical connection between the trolley wires of the overlapping sections except during the passage of the bow.

These sections are from 3,000 to 4,000 ft. long and the arrangement serves naturally as a section insulator around which a jumper can be placed if desired. On the line at Rotterdam the builders have cut the messenger wire at every bracket, inserting a strain insulator resting upon the bracket and composed of three insulators so that there are ordinarily two in series. This construction is shown in Fig. 14. Previous practice, as at Hamburg, (see Fig. 15) and Lancaster, England, adhered to the continuous messenger, but presumably the change was made in the interest of diminishing the effect of changes in temperature of the continuous messenger.

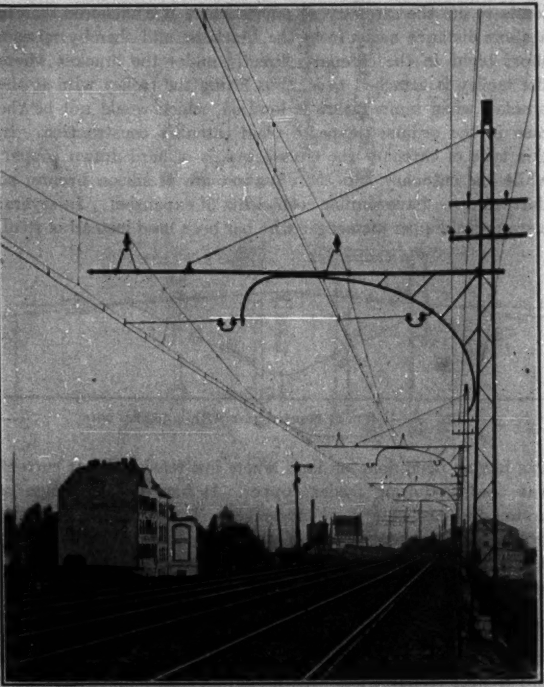

FIG. 15—Catenary construction at Hamourg

The latest improvement introduced in Europe for eliminating unevenness of operation due to temperature changes is a new design in which there is included an equalizer wire, so-called, which runs above the catenary between brackets without any intermediate hangers, as shown in Fig. 16. Being somewhat shorter and with less slack than the messenger wire proper it tends to lift the catenary at points where it is anchored thereto a short distance away from the brackets, and thereby raises a short bight in the catenary directly under the bracket where the trolley is attached to it, thus lifting the trolley wire at the bracket when temperature is lowered, which would not be the case in the ordinary type of plain catenary construction. In this type of catenary the trolley wire is of hard drawn copper, while the catenary and the equalizer are of silicon bronze, so that all three have similar coefficients of expansion. In several instances a copper messenger wire has been used instead of steel, this having been done on lines where low-tension direct current was used, requiring feeder copper. It has the advantage of saving the cost of a steel messenger. The fact that both the trolley and messenger are of the same material will greatly lessen the troubles that have been experienced with a steel messenger and a copper trolley wire.

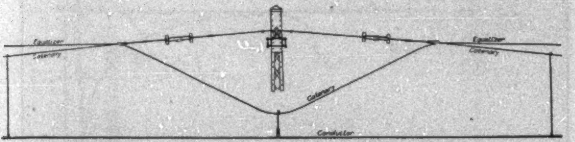

Fig. 16—Catenary construction with equalizer wire

The excellent service being rendered by steel trolley wire on the New Haven R.R. has suggested to the writer that it might be worth while to propose using a combination of a copper messenger and a steel trolley wire. In this arrangement the trolley wire would expand and contract less than the messenger and it would seem as though it should therefore be more easily kept at required tension. There has not been time to work up the idea in detail but it is submitted for the criticism of those who are interested. It will probably be more suitable for the higher than lower voltages, but as it is no more difficult to insulate catenary trolley construction for 11,000 volts than for 2,200 volts, the extra cost of insulation due to carrying the higher voltage is insignificant.

Catenary Hangers. There are so many types of catenary hangers that a description of all would be tiresome. Six different companies are each offering several different types of hangers, including both the messenger and the trolley clamps and the rod connecting them. For the plain type of construction there now seems to be a preference for a hanger that has an easy or flexible grip on the messenger wire and a powerful positive grip on the trolley wire, with a joint between clamp and rod, either at the

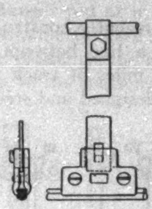

FIG. 17

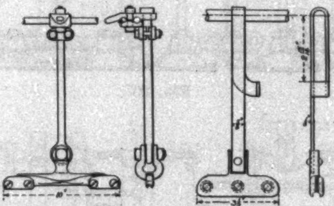

FIG. 18

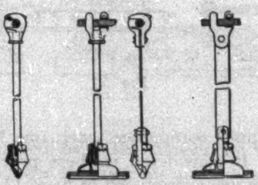

FIG. 19

top or bottom, or sometimes both, to increase the general flexibility. In the earlier work, four or five years ago, messenger and trolley clips were rigidly connected together and even in spite of the lack of experience in design and erection they operated very well in many cases, provided the trolley wire was pulled sufficiently tight.

The Connecticut Company recently constructed several miles of catenary construction on a line between Middletown and Hartford, Conn. About two miles of track were given up to trial sections of construction designed and erected by six manufacturing and supply companies, each one having a chance to erect that which it considered its best practice. Some of the designs of hangers are reproduced in Figs. 17 to 23.

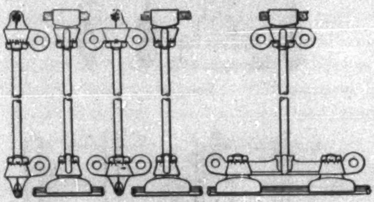

Fig. 20

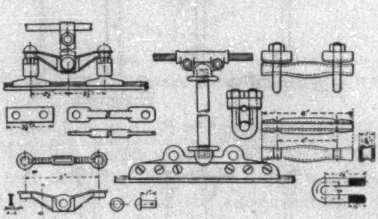

Fig. 21

It is safe to say that almost every engineer who has built a catenary line has tried his hand at devising a new catenary hanger that would combine simplicity, flexibility, certainty of grip, speed of application and adjustment, and cheapness. Fewness of parts is essential to cheapness and speed of adjustment. A hanger of five or six parts, including bolts and nuts, is preferable to one of ten or twelve parts. The grip on the trolley wire should be powerful and easily applied. One nut only should be allowed, to tighten or loosen the trolley clamp. The hanger shown in Fig. 24 seems to answer most of these requirements.

The writer's preference is for a nut screwing down on the lower end of the hanger rod as in Fig. 24, as it can then never work off. It is desirable to have at least one pivot joint in the rod, either at the messenger or at the trolley ear. The loop type of connection to the messenger wire where the top of the rod is practically looped over the messenger wire or forms a slot for the entire hanger to work up and down on the wire as in Fig. 25, has only one drawback and that is the possibility of wearing away the galvanizing of the steel messenger cable. If the messenger be of copper the wear would probably injure the cable mechanically. This type also has the advantage of permitting the endways movement of the contact wire which will allow its tension to be well equalized on different sections of the line.

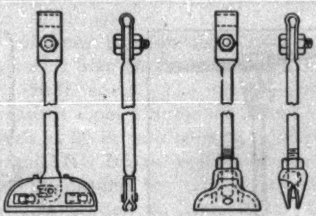

FIG. 22

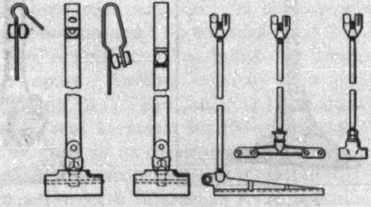

FIG. 23

In our hunt for the best imaginable solution it must not be forgotten that some existing solutions are operating very satisfactorily, and we may sometimes do well to call a halt and ask ourselves whether all these adjustment features are really worth while, particularly if they are costly.

There is one feature of catenary design that always deserves careful attention and that is the number of different lengths of hanger rods in a span. The average railway will have more or less curvature, and spans of different lengths on the same, in which the number of inches sag of the messenger will vary considerably, though the spacing interval of the hanger rods is ordinarily uniform no matter what the distance between poles or bridges. On the Erie R.R. electrification there was little curvature and the number of different lengths of span was limited, and only six different lengths of hanger rod were needed, with 10-ft. spacing. On the Denver & Interurban there was considerable curvature; the spans varied from 120 ft. down to 60 ft. in length, spacing 10 ft., and yet there were only six lengths of hanger rod required. Three of the manufacturing companies issue catalogues or instruction books dealing quite fully with catenary construction and from the three together one can pick out most of the mechanical details necessary for equipping a line, and much

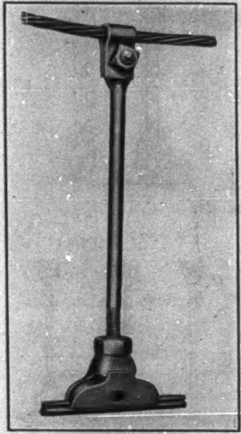

FIG. 24

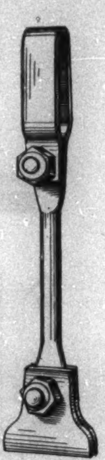

FIG. 25

valuable information is given that will aid an engineer greatly in laying out the work. But with respect to this matter of lengths of hanger rod, shown in these catalogues, it is found that for spans from 150 ft. down to about 70 ft. one firm shows 18 different lengths of hanger rods necessary to carry in stock, while another firm illustrating spans from 150 down to 55 ft., proposes only 11 different standard sizes. A third manufacturing company shows about the same range with 14 sizes. The Rochester, Syracuse & Eastern construction requires 11 sizes. There is thus always room for the exercise of judgment in reducing the number of parts.

The vertical distance between the messenger and trolley wire at the brackets is from 20 to 23 in. on 150-ft. spans and 17 or 18 in. on 120-ft. spans. The minimum distance in the center of long spans is about 4 in. for 150 ft. and 6 in. for 120-ft. span and as much as 20 in. in a 60-ft. span when the interval between hangers is 15 ft. It is noticeable that there is a tendency toward increasing the distance between hanger points in catenary spans. It originally started at about 10 ft. One company, during the early development advocated three-point suspension on tangents for spans as long as 150 ft. At the present time however the three-point suspension is only recommended for wheel trolley operation and 11-point suspension is recommended for sliding bow operation. This brings the hangers approximately 14 ft. apart. Another company shows spans varying between 10 ft. and 13 ft. 7½ in. which is 12 points of suspension for 120-ft. span, and 11 points for 150-ft. span, as desired. A third company gives in its catalogue fittings designed for 10-ft. and 15-ft. spacing, on spans from 60 ft. to 150 ft.

The American Street & Interurban Ry. Association's Committee on Power Distribution prepared a report on catenary construction in 1908 and its conclusions were rather in favor of hanger spacing of 20 ft. to 30 ft. because the sag between hangers, though very slight, would still be sufficient to help take up the expansion of a copper trolley wire in warm weather. It was quite evident that the committee hesitated to recommend the complication of the compound catenary type of construction if any means could be adopted that would accomplish reasonably smooth operation with plain catenary construction. It also reported very favorably on making spans 300 ft. in length; that the hangers should be as light and flexible as possible and that the messenger cable should be of plow steel, strung to a small sag.

Much is said from time to time about the necessity of staggering the trolley wire from side to side when constructing for sliding bow operation. The writer has noted enough successful operation without staggering, to confirm his belief that it is not absolutely necessary under interurban conditions with average track, and motor cars of the usual interurban style. With these conditions the car is generally so sure to sway from side to side as to equalize the wear fairly well on the sliding bow. It is only where there are very heavy locomotives and extremely solid track and roadbed that the writer would entertain seriously the necessity of staggering the wire, but though these conditions are present on the New Haven Road, the contact wires have not been staggered. Unless great pains are taken to prevent it a staggered wire always tends to pull straight and consequently to induce some sag that is not desired.

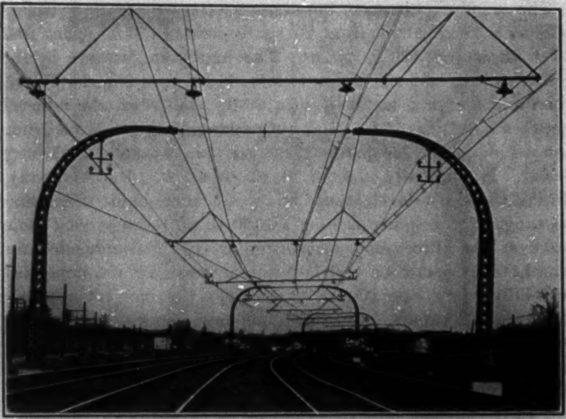

Fig. 26—New catenary construction of the N. Y., N. H. & H. R. R.

The new design of heavy catenary construction developed last year by the New Haven road is a remarkable advance in several respects, and is illustrated in Fig. 26. The chief points of interest are the following:

1. The supporting bents are much more sightly and more economical of material than the original bridges.

2. The main suspension cables of 1¼-in. stranded steel wire which carry the insulators and the messenger wires proper are uninsulated and grounded, which will facilitate maintenance, painting, etc., and will obviate much of the danger to men on the signal bridges.

3. Insulators, if broken, can be replaced by removing only three bolts, the two by which the insulator is suspended from the crossbent and the one which suspends the messenger wire from the insulator.

4. The feature of a steel working trolley wire below a copper conductor, using the spring in the upper wire to permit the contact wire to yield in an upward direction, is here developed, showing it to be regarded as a successful means of securing smooth and reasonably flexible contact.

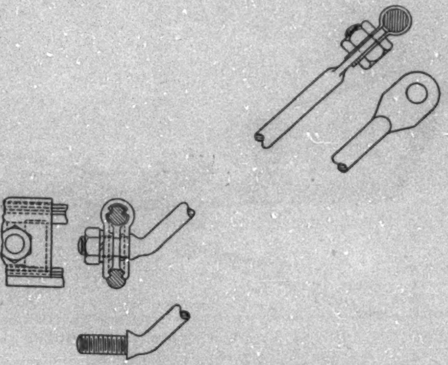

Fig. 27—Bent inclined hanger rods

5. The necessity for steady-strain insulators and pull-offs of the previously accepted types on curves is entirely done away with because the hanger rods are so dimensioned that, by inclining them at such an angle that the trolley wire follows the alignment of the curve exactly, the tendency is for the lower wire to pull to a curve of shorter radius than the messenger wire. By adjusting the lengths of the hanger rods with some care the curve of the center line of the track can be closely approximated by the lower ends of the hanger rods when thus inclined

and rightly adjusted for length. By bending these inclined hanger rods so that their bottom ends are horizontal, then passing the horizontal end through the middle of the clip that fastens the contact wire to the secondary messenger, the two latter are held rigidly in a vertical position and the working trolley is maintained as exactly under the secondary messenger as though it were on a straight line. See Fig. 27.

The criticism is sometimes made of steady-strain insulators for catenary curve construction that the tension under which they do their work makes the curve rigid and unyielding. In this case the heavy steady-strain insulators are dispensed with altogether, being replaced by the light iron hanger rods which for the time being are acting as steady strain insulators. Their greater frequency must minimize the pull of each individual rod and tend to make the whole structure less rigid than where steady strain insulators or pull-offs are applied at intervals of 30 ft. to 60 ft.

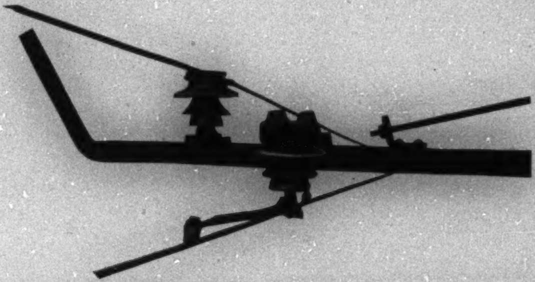

FIG. 28—Steady strain insulator, Denver & Interurban Railway

6. The adjustments for height in this construction are extremely simple, being accomplished by slipping the suspending members of the cross bents nearer to or further from each other along the bent, thus raising or lowering it.

The features here mentioned can all be easily noted in the illustrations and should appeal as only a first-class mechanical job can, to every engineer who has had to deal with overhead construction in general and catenary in particular.

Steady Strain Insulators. Steady strain insulators usually consist of a stick of treated wood shaped like a long strain insulator, terminating at the outer end in a hook-shaped fitting that is attached to the trolley car, being pivoted at the inner end to an insulator on the bracket. When in this form they must be inclined upward away from the trolley wire so as to clear the sliding bow. While originally intended for curve construction only, it is often found desirable to install them at intervals along tangents say from 5 to 10 poles apart, as their presence helps to prevent swaying of a suspended trolley wire in a very high wind.

The form of steady strain insulator used on the Denver & Interurban Ry., is shown in Fig. 28. This has the merit of employing the same kind of 11,000-volt insulator that is used on the standard straight line catenary support, the head of which is cemented into a socket on the end of a malleable iron bolted to the bracket. The brace proper is a short link of malleable iron loosely hooked into an eye-bolt projecting from the bottom of the insulator. It will thus swing through an arc permitting some longitudinal movement of the trolley wire. In case the insulator breaks it will fall to the ground from the outer end of the hook, and the hook is light enough so that the stiffness of the trolley wire will make it stand out straight after the insulator has fallen and it will not hang down and foul the sliding bow.*

Between poles, various schemes for pull-offs are used, but the commonest method is to run a bridle from the upper and lower ends of the hanger spacing rods, joining the bridle wires at some distance away from the trolley and insulating the pull-off by a strain insulator. Sometimes a wood strain insulator may be put into each of the bridle wires, but care must be taken not to weight them down so that they would be in danger of fouling a bow trolley. Probably the best way to insulate a pull-off for high voltages is to use the disk type of strain insulator, which was first brought out by E. M. Hewlett in 1907. This is the handiest form of light-weight porcelain insulator and fits nicely into almost any pull-off situation. A porcelain spool has also been used as a pull-off insulator, to slip over a hanger rod. This adds weight to the trolley wire and may make a hard spot, which is undesirable for bow trolley operation if located at a point where high speed is to be made, but it is not especially objectionable on a siding or in a yard and it insulates every inch of the pull-off wire and is probably the cheapest form of pull-off for high voltages. The pull-off wire is attached directly to the middle of the spool.

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* This device has been patented.

Strain Insulators. The writer's experience with catenary construction having been with high voltages, it has been necessary to be particular about strain insulators.

After some unfortunate experiences with strain insulators built up of metal and moulded insulating material of one form or another, it was found that porcelain, if it could be kept in carefully equalized compression, was the most reliable insulation, and as in the case of the straight-line insulators, a single insulator (of the heavy porcelain spool type), properly mounted, can always be depended upon. The easiest way to mount such insulators is to cement them upon a piece of pipe large enough to carry a ⅞- or 1-in. bolt. If the bore of the spool is fairly large it may be necessary to use 1½-in. pipe. It is more necessary to have the pipe nearly as large as the insulator than it is to have the bolt nearly fit the pipe.

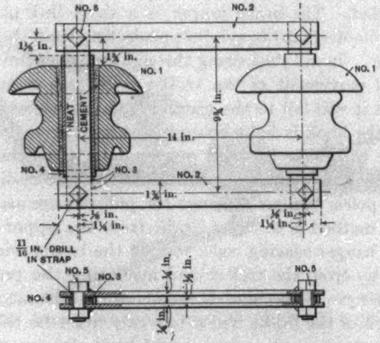

Fig. 29—Double spool strain insulator

The disk type of insulator is very ingenious, light and attractive but the body of the porcelain under compression is not sufficient to resist a crushing strain of more than 5,000 or 6,000 lb., or it was not when certain tests were made under the writer's supervision between two and three years ago. The 6½-in. diameter disk insulators are now advertised to carry a safe working load of 2,500 lb. and the 10-in. insulator 4,500 lb. With the trolley tension sometimes reaching 5,000 pounds at low temperature, a strain insulator for dead ending must have a working capacity of at least 7,500 to 10,000 lb., and it ought to be as high as 12,000 to 15,000 lb. This puts the disk type out of the running. The writer designed for the Denver & Interurban a double spool insulator comprising a porcelain spool cemented on 1½-in. pipe with 1½ by ½-in. flat iron driven through the pipe and standing edgeways to the strain, there being a hole in each end of the flat iron for linking to the other porcelain similarly fitted. This insulator, under test, carried 50,000 volts and 14,000 lb. strain simultaneously, without failure. It is shown in Fig. 29.

It is the writer's belief that, even more than in the case of direct suspension, strain insulators for catenary construction should be specified to be tested mechanically and electrically at the same time, up to their maximum mechanical and electrical capacities. It is only in this way that actual conditions of service can be duplicated in a test.

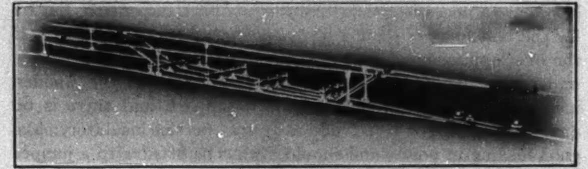

FIG. 30—Deflector

An excellent point about the disk type of insulator when used within its capacity is that there is a mechanical linkage of the guy cables on opposite sides of it which prevents their falling apart if the porcelain burns. This is not true of a wood strain insulator, which under high voltages is much more likely to get burned in two than at low tension, and for this reason the writer does not believe in using wood strain insulators for heavy strains where there is any possibility of a full voltage being applied to opposite ends of the insulator.

Deflectors and Frogs. The deflector is illustrated in Fig. 30. This contrivance has sometimes been found necessary to prevent the horns of the pantagraph bow trolley from getting tangled in the wrong wire where two trolley wires intersect on a switch or crossing. If the bow has no horns or if the horns are prolonged downwards there is no danger of a bow catching and no necessity for the deflector. In fact deflectors are about the worst nuisance one has to contend with in maintaining a catenary line, and even where they have been carefully installed they are very apt to give trouble. It is very difficult to stretch the intermediate wires perfectly tight, and to keep them tight, even after they are adjusted.

The use of frogs on catenary construction for a sliding bow is unnecessary and when so installed they have usually been taken out afterwards.

Deflectors are heavy enough to require considerable care in setting them up, and on account of their weight, it is desirable to have them under a bracket or as near as possible to one. If not kept in good trim a bow trolley rapidly traveling underneath one will cause more or less flashing, which sometimes spreads up to the bracket, grounding the line and throwing the current off for the time being.

Section Insulators. With wheel trolleys, wood section insulators are a necessity, as in the case of direct suspension, but by far the best form of section insulator for bow trolley operation is the overlapping break without any wood or any other insulated under-run. They are also cheaper to install than the wooden insulator, there is far less weight to support, and there is no danger of warping or of destruction by fire. Section insulators make good feeding-in points and should always be fitted with a jumper which includes a knife switch, usually kept closed. When it is desired to open a section of high voltage trolley a hooked stick with a grounding chain attached above the handle is used to pull the switch, being kept hung permanently in the switch box which should be well up on a pole out of reach of all but employees. It is desirable to have such switch boxes located at railroad stations or signal towers.

On two important installations of 11,000 volts, with multiple unit car operation, no feeder wire has been found necessary and section insulators have been introduced mainly for subdividing for the purpose of more readily locating trouble. The best information for computing trolley drop in a single phase railway, and calculating feeders, is to be found in Mr. A. W. Copley's discussion of Professor Whitehead's paper on "From Steam to Electricity on a Single-Track Road," in the A.I.E.E. PROCEEDINGS for 1908.

Lightning Protection and Ground Rod. It is absolutely necessary at high voltages to ground all the brackets and spans of a catenary line. This is most effectively done by steel or iron bars about $\frac{5}{16}$ or $\frac{3}{8}$ by $1\frac{1}{4}$ in. with the top end bolted to the butt end of the bracket and the bottom end run over to the track through the ground from the butt of the pole. The best kind of a connection to make with the track is through a cross bond, as this is more flexible than to connect a rod directly to one of the rails. The ground rods, brackets and truss rods together form a pretty fair lightning protector for the trolley construction, but to make it more effective, on the Denver & Interurban Ry. a $\frac{7}{16}$-in. steel ground cable was run on the tops of all the poles and connected to every bracket and at every fifth pole a ground rod was run down the pole and attached to a cross bond and also to a pipe or a plate ground, the latter being used when there was any moist earth near at hand. This general scheme is the cheapest method of combining the grounding of brackets and lightning protection and it has an additional advantage of stiffening the pole line considerably.

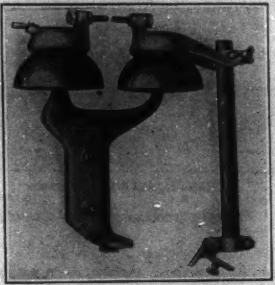

FIG. 31—Fuse type lightning arrester

If circumstances make the use of line lightning arresters desirable, the swinging fuse type shown in Fig. 31 may be installed at intervals of a half mile. This arrester has given good service for three years on the Erie railroad, at 11,000 volts.

Splices. For a trolley wire at ordinary tension, the old forms of splicing sleeve did fairly well, but where the tension is great and the wire very stiff, as with phono-electric or steel wire, the old form of sleeve, with the necessity of curving the wire slightly in order to get it through, is inconvenient, especially for quick emergency work. A sleeve with both holes bored perfectly straight and inclined slightly upwards toward the center will allow the trolley to enter and pass through without binding. To insure sufficient strength, this type of sleeve is made out of rolled bronze about 1 in. square with rounded edges, as shown in Fig. 32. Experiments showed that it was not safe to depend upon a mechanical splice that involved bending trolley wire beyond the elastic limit, although such a splice would be very quick and easy to make. For splicing messenger wire, use is made of cable splicing sockets shown in Fig. 33. To absolutely prevent the messenger wire from pulling out, the ends of the strands were doubled back on themselves, the cable end pulled back hard into the socket, and babbitt poured in.

Moving Contact. It is the writer's impression that the high voltage catenary construction now in use is in nearly all cases operating under conditions favorable to the sliding bow. The conditions on the New Haven road are doubtless more severe than any other as they involve high speeds, many low bridges, and the heaviest currents yet demanded in alternating-current railway work. On nearly every other single-phase alternating-current railway the traffic is in single-car trains, or with much lighter locomotives, and at lower speeds. More skill and judgment are needed to erect and maintain catenary than direct suspension, and experience shows that the fundamental difficulties preventing smooth operation arise primarily from the expansion and contraction due to changes in temperature, which must be overcome by following some of the methods herein suggested.

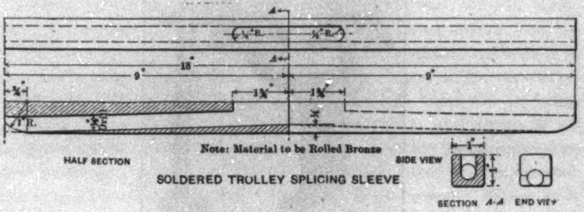

Fig. 32

Barring the tendency of the old fashioned trolley wheel to jump at high speed, even on fairly well aligned wire, it has proved a reliable contact maker up to the limit of its capacity, and has shown itself readily adaptable to all conditions of sag in long spans. The gradually increasing use of the catenary construction with the wheel trolley, a combination which seems to be well thought of by railway operators, encourages the writer to believe that in the heavy railway work of the future on trunk lines or over long distances, where high voltage alternating current is the obvious solution, the rolling contact will tend to reassert its superiority over the sliding bow. The manufacturing companies, to whom engineers generally look for progress in such matters, cannot be said to have made much progress in this direction during the last few years. Although the writer has not been in a position to conduct any experiments with the roller type of trolley, nevertheless, in the absence of convincing proof to the contrary he is disposed to believe that it may yet be so developed as to constitute a distinct improvement over the present sliding bow, in the rough and ready service which the trunk line work of the future is sure to require.

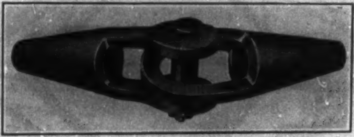

FIG. 33—Cable splicing socket

As has been the case before in some practical electrical matters, progress in this respect has (in the U. S.) had its start on the Pacific Coast. On the interurban cars of the San Francisco, Oakland & San Jose R.R. there are now in use pantograph roller trolleys of the type shown in Fig. 34. "The roller for these trolleys, which is held against the wire by a spring connected with the pantograph, is a brass cylinder 5 in. outside diameter and ⅛ in. thick. The pantagraph has a vertical movement suitable to accommodate the rise and fall of trolley wire 14 to 22 ft. above rails. This type of trolley requires little attention and the brass cylinders show an average life of about nine months on cars making 250 miles a day."* These cars are working on 600-volt direct current and have four 125 h.p. motors, so that the roller trolley evidently carries quite a respectable current. It is to be hoped that the heavy alternating current locomotive work of the future as well as the multiple unit car operation can be made even more successful than now, and the wear and tear on trolleys and line construction diminished, if the development of the roller contact trolley can only be given the attention to which it seems entitled.

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* Quoted from the *Electric Railway Journal*, Oct. 2, 1909.

The life of 67,500 miles for pantagraph roller trolleys, computed from the above quotation, seems incredible, and in the absence of detailed records may be somewhat discounted; but it is quite evident that the device is worthy of consideration. The life of pantagraph shoes is variously reported as all the way from 8,000 to 15,000 miles on single-car interurban lines, and very much lower than this on the New Haven road, where the conditions of high speed, heavy currents, more rigid trolley construction and low bridges, all combine to wear them out rapidly.

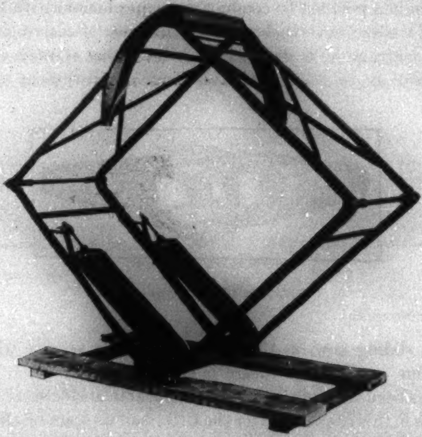


Fig. 34—Brown pantagraph roller trolley

Double Trolley Construction. The writer has paid no attention in this paper to double trolley construction as distinct from standard types, because it is used so little in the United States, either in direct current or alternating current systems, that it is not at present a matter of very great interest. Where used, it is generally erected with the same types of overhead material as are used in single trolley construction.

The Europeans have worked it out for three phase alternating railway equipment with all the care and neatness that characterizes their construction. They seem to be willing to put up with more complications in the accomplishment of results than does the average American engineer, and the principle of adherence to form rather than simplicity in attaining a result seems to prevail both in the personal side of railway administration and in the development of mechanical and electrical ideas. This temperamental difference is further manifested in the much greater respect shown by Europeans than by Americans for law, rules, and formulæ of every kind. While the American character would doubtless profit by stricter discipline in the matter of legal observance, there are some aspects of close adherence to theoretical rules and precedents which are essentially in conflict with the necessities of American railroading, and it is very doubtful whether any American railroad man will ever become reconciled to erecting two trolley wires of opposite polarity over any railroad track, if he can possibly get along with one.

It is the writer's opinion that this one condition more than any other, will retard three-phase railway development in this country. The discussion of Dr. Hutchinson's recent interesting paper on the three-phase electrification of the Cascade Tunnel indicates that while the three-phase motor was very well adapted for slow speed locomotive duty, the only really unsatisfactory element in the equipment was the overhead construction, though this was partly due to certain conditions imposed upon the engineers by the railroad authorities. Single trolley operation over steam railroad tracks has now been carried on for so many years as to be practically commonplace even among railroad men; and an object lesson of a more universal type than the Cascade Tunnel will have to be presented in working order, before the present convictions of American steam and electric railway operators, with respect to the double trolley, can be changed.

In considering the development of heavy electric traction on trunk line railways, therefore, we are brought back to our starting point by the controlling influence of the working conductor:—namely, that it is the trolley system rather than the motor which is the characteristic feature of a railroad, and that that type or system of motors will ultimately prevail which can utilize the cheapest and most easily maintained working conductor for the required conditions of operation.

At the conclusion of this paper six lantern slides of European catenary construction from illustrations kindly furnished through the courtesy of the *Electric Journal* and Mr. R. A. Hellmund illustrating the latest work in three-phase electrification on several sections of Italian railways. These views are published in the *Electric Journal* of May and June, 1910.

There were also shown four other views of American catenary construction on the Erie R. R. and elsewhere, including the original overhead Z-bar construction of the Baltimore & Ohio tunnel installation, which was built on the catenary principle in 1895.

For much valuable information and many of the illustrations given in this paper, the writer must acknowledge his indebtedness to Mr. J. J. Brennan of the Ft. Wayne & Wabash Valley Ry.; to Mr. T. H. Mather of the Rochester Syracuse & Eastern Ry.; to Mr. R. C. Thurston of the Erie R. R.; to Mr. H. W. Cowan of the Denver & Interurban R. R.; to representatives of the General Electric, Westinghouse, Ohio Brass, and Electric Service Supplies companies, to the *Electric Railway Journal* and to Westinghouse, Church Kerr & Co.

DISCUSSION ON "THE APPLICATION OF PORCELAIN TO STRAIN INSULATORS" AND "ELECTRIC RAILWAY CATENARY CONSTRUCTION", NEW YORK, MAY 27, 1910.

Percy H. Thomas: Mr. Kempton's paper gives us some actual tests on porcelain. We have had almost no data hitherto on the mechanical qualities of porcelain, quantitatively speaking. The manufacture of porcelain has been a secret, a mystery, and engineers have taken what was offered by the makers, taking the catalogues and selecting the best design for their purpose among those offered.

We here have a beginning of figures on the compressive, tension and other strength of porcelain as a material, some of the same sort of data as we have on steel and wood.

The compression strength of high grade porcelain is relatively very great, 16,000 lb. or thereabout. The average shearing stress here is given as 2400 lb. per sq. in., and the tensile strength as 650 lb.

This relationship between the various sorts of strength in this material dominates the form of design. We are very familiar with the shapes of insulators shown in the paper. There is one example among those of an important type of insulator in which is used the weakest quality of porcelain, and that is the suspension type of insulator, similar to Fig. 9 of the paper. This is a matter of which we should think pretty carefully.

I want to make a suggestion in connection with Fig. 9. That insulator shows porcelain in tension, as this design is made, and as the failure under test is described this insulator had better be made in some different proportion.

As shown in the paper we have a fracture at the bottom of the cap, that is across from the top of the inside pin to the bottom of the outside cap. The result is then only the tensile strength of the porcelain is utilized. If on the other hand, the insulator had been shaped differently, the pin being carried well up inside, with a deep metal cap taking hold well down on the insulator, since the pin cannot pull out without crushing the porcelain.

These tests, while they give some numerical figures are faulty in one particular. Mr. Kempton has apparently taken some insulators which he had at hand for making tests, and these show numerical results for those particular forms; but in no case are the tests such as to give us a clear knowledge of the materials as materials. Some of the insulators broke at the edge. In Fig. 3, the shearing test, there must be some tendency to split the insulator as shown; perhaps not much, but enough to render this data uncertain.

I remember some tests on one of these suspension types of strain insulators, such as No. 9, which gave a tension strain, roughly two or three times as great as Mr. Kempton has given. Possibly Mr. Kempton can say something on this subject at the end of the discussion.

There is another point which should be determined further by tests before any final conclusion is reached, and that is whether materials made by different manufacturers and materials of different compositions and treatment, will show the same unit of strength?

This would be an admirable thesis for some post-graduate work at a university or college. It is difficult for engineers in general practice to make a careful general study.

We seem in the matter of insulators to be arriving at the condition which finally comes in all new classes of work. At first designs are on the hit or miss principle but finally after sufficient investigation, reliance in made on a few of the old simple, practical, fundamental laws. For example, it is an old principle to take account of unequal expansion. The cementing in of metal pins in the strain insulator, may lead to trouble where expansion is serious. Again, if you do not allow for differences of flexibility in different materials, there is a strain on the porcelain. These matters are easily overlooked, but they are the simple principles that should have been borne in mind from the beginning.

It is often suggested that the way to get reliability in insulation, is to increase the margin of safety. This can be done quite easily in overhead railroad work where the trolley voltages are low; by choosing a factor of safety of five instead of perhaps three. This, however, is not very possible at 100,000 volts or even at 60,000 volts. Where feasible is thus possible to gain superiority and reliability at only small additional expense.

I ask Mr. Kempton a question: It is well established that a high tension porcelain insulator, 60,000-volt petticoat type, can be *shattered* by a lightning stroke without the puncture of the material, and without any arc following from the generator. This seems to be caused by something in the nature of a mechanical shock. The result is often the dropping off of the outer petticoat, it being broken close to the stem of the insulator.

I also ask Mr. Kempton if he has any suggestion to meet this condition. The phenomenon is reported at the Taylor's Falls system, and on the Ontario Power system. These are two thoroughly authentic instances. How can this strain be resisted?

Considering Mr. Smith's valuable paper, I would like to have his opinion as to the practicability of obtaining sparkless action in pantagraph trolleys by having a relatively light piece on the top of the pantagraph which shall have the least possible inertia. The heavy arms would then not be required to follow every slight movement of the sliding contact.

C. J. Hixson: It has been most interesting to have Mr. Smith trace the development of the catenary construction and listen to his comments and descriptions of the various devices used in connection with the same.

It has been stated that catenary construction was first brought out in 1904. In 1903 while connected with the Allgemeine Elektricitats Gesellschaft, of Berlin I remember discussing and inspecting with visiting Westinghouse engineers, the catenary line installed by the Union Elektricitats Gesellschaft upon a branch of the State Railway known as the Nieder Schonweide-Spindlersfeld line. In October of the same year, the *Street Railway Journal* published an illustrated article describing the installation. I have no doubt Mr. Smith meant, that it was first used in this country at that time.

In Mr. Smith's comments regarding catenary developments abroad, and the improvements upon the New Haven System, as well as the experimental line of the Connecticut Company, he states there is a general feeling of satisfaction with these constructions. It is significant that all of these have a more or less flexible trolley wire.

This vertical flexibility of the trolley wire is, it seems to me, the keynote to the successful collection of current from a trolley wire.

The general conditions of stability and of sidewise anchorage, limit the vertical flexibility to a few inches, and it is necessary to assist this flexibility by frequent supports or hangers

The height of the wave in the trolley wire as the collector passes along should be such as to take up all the sag between hangers and still raise the hanger a couple of inches as it passes under it.

The lifting of the hanger to a floating position eliminates the blow that would be delivered to a rigid support. Catenary hangers rigidly connected become increasingly hard as the bracket arm is approached. With a flexible hanger the increased and ever present flexibility at the point of contact, compensates in a measure for the inherent sluggishness of the roller pantagraph so complimentarally referred to in the latter part of Mr. Smith's paper.

For very heavy currents with two trolley wires side by side vertical flexibility is of great assistance in keeping the necessary contact pressure down to a modest figure and yet maintaining continuous contact with both wires at all times.

In order to have vertical flexibility the strain in the trolley wire should be moderate say from 1200 to 1500 lb. With this tension, with hangers 13 feet apart and with a No. 4/0 trolley wire, a vertical flexibility of an inch or so can be attained with an upward pressure of about 7 lb. This reduced tension in the trolley reduces the strain upon pull-offs, anchorages, strain insulators, and the line in general, thereby decreasing the original cost and the cost of maintenance.

In order to maintain the tension between reasonable limits at different temperatures provisions should be made for taking up the slack without disturbing the hangers and pull-offs.

The trolley wire is held best on curves by frequent pull-offs. This gives maximum flexibility with low stresses and moderately strong strain insulators. On earlier installation steady braces were used, but they have now been superseded by either flexible pull-offs or line steadiers. A steady brace when used as a strut gives a hard spot in the trolley wire.

Regarding pole spacing on curves, the table given is, we assume, designed to be used with no other points of pull-off than a steady brace at each pole. It is possible to maintain this same offset of the trolley wire from the center of track and use a longer pole spacing by running a back bone and using more pull-offs. This also makes a more flexible construction. If the curve happens to be on the side away from the pole line, a bracket extension can be used to support the backbone.

In conclusion it might be said that a single messenger flexible catenary has been in successful operation for the past two years upon the Saratoga Division of the Schenectady Railway. There has been no sign of wearing the galvanizing on the messenger wire due to the movement of the loop, as the sides of the same seldon if ever more than just touch the messenger wire.

R. D. Coombs: Before attempting to say anything about the experiments made by the Pennsylvania Tunnel and Terminal Railroad about two years ago, I might call attention to a few general facts, or rather, general considerations.

Since the track on which the equipment runs is not a plane, but a series of vertical curves, I think that it is entirely unnecessary to attempt to keep the trolley wire perfectly horizontal. The equipment will not run in a plane, and so I cannot see why it is necessary to keep the trolley wire in a plane. That is aside from the fact that you cannot do it.

The question of flexibility is as yet very uncertain. The Germans have used a secondary catenary, and according to their statement it is entirely successful, but their speeds and trainloads are less than our own. The experiments to which I referred a moment ago seem to indicate that a single catenary with a very light hanger, composed of a flat section, 1⅛ in. by $\frac{3}{16}$ in., looped over the messenger, and with the ordinary type of ear, was about as successful during the limited range of those experiments, as the German type with the auxiliary catenary. I am inclined to believe that a light hanger particularly in conjunction with a trolley wire having considerable stiffness and strength, possibly a steel trolley wire, as I believe was used on part of the New Haven installation, with either a copper messenger or copper feed wire to provide the necessary conductivity, would be a combination worth very careful investigation, and perhaps some experimentation.

The little hanger which loops over the secondary wire and attaches to the trolley wire, permits vertical movement, but seems to have a tendency to roll. On a portion of the experimental line, in putting up the trolley wire, it was found that the trolley wire had a twist or roll in it; and that the little hanger above the ear rolled laterally, and became to a certain extent, bound, particularly at a pull-off. That same criticism, it seems to me, would apply to one of the figures in Mr. Smith's paper. I refer to Fig. 27. I should expect that inclined hanger, which is the same as a pull-off in effect, to roll, and I ask Mr. Smith whether that tendency has been experienced?

I am rather inclined to question whether it is necessary to pull the trolley wire to an excessive tension; and I believe that to be a subject which requires more investigation. I think the rigidity, and the tension of the trolley wire, the rigidity of the catenary above the trolley wire, and the flexibility or "intelligence" of the pantagraph should all be considered together; and that the failure of no one of them should be allowed to prejudice the particular arrangement of design.

Until these features are all brought into a harmonious relationship, no single arrangement can be termed saitsfactory. The pantagraph has always seemed to me to be a suitable field for experiments, and it should be noted that the secondary flapper, according to the statements of the German engineers, has given entire satisfaction abroad.

Director Freishmuth of one of the German companies, told me on his visit to this country about two years ago, that their auxiliary arrangement on top of the pantagraph, gave entire satisfaction, and that it did not spark. Their speeds are less than ours, and I believe their train-loads are also less; but if these pantagraphs have given the satisfaction abroad which it is claimed they have given, it would certainly seem that the pantagraph is a field for further experimentation and improvement.

Fig. 14 shows the messenger wire broken at each support, that is, each span, is a unit in itself, the advantage of which Mr. Smith questioned. I believe one reason is that the short span can be assembled on the ground, the hangers placed, and the end socket can be done either on the ground or in a convenient shop. It does not require an aerial operation.

The combination of the steel trolley wire and the copper messenger is in use on the New Haven and it was to be tried on the experimental line. It was not installed, but it was because of no lack of faith in it as a device. I believe the grease from the pantagraph shoes, or a system of greasing the trolley wire will prevent any rust.

The loop, attaching the hanger to the messenger wire, in case a loop is used, should be properly fitted at the top in order to allow the hanger to be vertical.

I do not think I can add anything in a very definite way, insofar as the results of the experimental line are concerned. It was necessary to put up comparatively short sections of different types of supports, different types of suspension, and different types of catenary. And as a result there was not a sufficient length of any one type to produce a determinative test. The locomotives passed rapidly from one section to another and it was almost impossible to ascertain on which section the wear of the pantagraph shoe occurred. The relative wear could only be inferred by observation of the action of the pantagraph on a given section. At the same time it was possible by observing the action of the different types, to determine with more or less accuracy, a certain degree of relative merit.

The experiments did not continue through a round of seasonal changes, and definite results were not obtained, but I am inclined to question whether on long spans, there is any objecable action due to the tensional changes. The German construction, with the tension devices by which the wires are automatically kept at a certain tension by weights at the supports, were used, but no definite results were obtained. We obtained just as satisfactory service on sections where the device was not present.

R. C. Thurston: During a high wind and from the rolling of the car, unless the wires are in ideal condition, there is a good deal of slack wire, which will cause the trolley or the pantagraph to go to one side and dip, and while over, allow the ends of the shoe to hit the cross arm. If the wire was perfectly tight, this would not happen. When our road was first installed, we had no such trouble, but after the heat of summer and the cold of winter had expanded and contracted the wire, there was slack. But owing to the expense and the lack of time between trains, it is not always advisable to pull a slack wire tight.

The spacing rods are clamped tight to the messenger wires. I believe there should be a loop at the top of the spacing rod to allow the spacing rod to slide along the messenger wire, as the slack in the trolley wire would not then form the kinks in the trolley wire that it does now.

We have had several bad cases of brakes in the copper wire and the brake is not sudden, we found it to be an old fracture, which was probably caused by the pounding of the shoe. As these breaks do not occur in cold weather, it shows they were not from contraction of the wire through cold. The break is always formed after the car has passed over, and it always caused us to put a splice in the wire.

Chas. R. Harte: It is too often forgotten that the overhead construction of an electric railroad serves in two capacities.

As a conductor by which energy is transferred from the central station to the collecting device of the motor its function is simple and well understood; that it is also the track upon which the collector travels at high speed is a fact too frequently ignored, although it is in this latter capacity that practically all of the serious problems and difficulties arise.

In the case of a railroad, light rails laid on soft ground, where a marked displacement wave precedes the train, will, within their load capacity, give as smooth riding, and will require as little maintenance as the hundred pound rail on stone ballast as unyielding as possible. But if in either class of track there is permitted to occur a spot of opposite nature, so that there is an abrupt change in the character of the displacement wave, there immediately follows rapid wear and serious injury.

Precisely the same results are manifested under similar conditions of the overhead; a hard point in an otherwise flexible line, or yielding spots in a rigid trolley at once develop kinks, crystallization occurs, and presently the wire breaks.

Up to the present time developments have indicated that the flexible line is easier of attainment than the rigid type; the writer believes, however, that the possibilities of the rigid construction have been by no means exhausted, and hopes to see further experiment in that direction.

The unfavorable condition is that in which whatever the cause, the trolley wire tends to bend on a short radius. In the earlier lines the comparatively large sag gave a large intersection angle at the points of support, and the clips being straight and short caused kinks in the line, in passing which the collector tended to momentarily reverse the bend on the approach side, and to deliver a sharp blow against the opposite side. The supposed necessity of eliminating the large sag led to the development of the catenary construction, as pointed out by the author. But, and this would seem to be the point urged by Mr. R. D. Coombs in his discussion of Mr. Smith's paper, a truly straight trolley wire is by no means a necessity. It is not the amount of the intersection angle at directional changes, but rather the shortness of radius of the enclosed curve that causes injury. With a long radius bend, and a type of support which would either gradually damp out the displacement wave or would transmit it without material interference, a heavily sagged trolley ought to give excellent service under severest conditions. Such a type of suspension, employing spans of two hundred and forty feet with a sag of thirty inches, the wire being carried in a curved ear of special design and some forty-four inches long, has been proposed by Mr. Joseph Mayer, Consulting Engineer (see Transactions American Society of Civil Engineers, Volume LXI, page 5) but so far as the writer is aware, has never been actually tried out.

The author, in describing double catenary construction says: "The excessive rigidity of this type has been found undesirable in practical operation". As an unconditional statement this is open to question. It is quite true that the first installation of this type to receive a thorough tryout was not entirely satisfactory, but the difficulty arose from the fact that while the hangers were very rigid, the line between yielded. At the critical speed the resultant chatter of the collector became synchronous with its period of vibration, and the line received severe punishment from the heavy blows of the pantagraph, in addition to the tendency to crystallization from bend reversals. The difficulty was most successfully overcome by duplexing the trolley, attaching the lower wire to the old trolley only at the centers of the secondary spans, but it is at least open to question if equally good results would not have obtained had the line been made uniformly rigid by the use of a tee or similar stiff section attached to the hangers.

As pointed out by the author, the question of the side clearances of poles is very important on electrifications and particularly so on railroads with black signals. Eight feet from center of track to face of pole brings the latter practically in line with the signal mast in its usual position and the engineer or motorman is hedged by an apparently solid wall of poles, behind which except as it is very near, nothing can be seen. Certain types of signal employ a centrally pivoted blade, half being in front of the mast, to obviate this difficulty of sighting, but even for this, ten feet clearance from track center to face of pole is little enough.

The author's conclusion that the trolley wire should very closely follow the center line of the track will have the endorsement of practically all operating men, particularly if qualified by the further proposition that for wheel work the center of track is to be considered projected through the center line of the car, in order to meet the offsetting of the wheel by the super elevation of the rail. This same offsetting affects the lengths of brackets on curves particularly if the poles are on the outside, in which case the bracket bar will often have to be materially longer than the standard.

Operating men generally will further agree with Mr. Smith that the irregular and unavoidable cross motion of the shoe, due to various car movements and sways, entirely obviates the necessity—and most undesirable complication—of staggering the trolley wire to prevent localized wear on the collector.

To secure the desired alignment on curves the preference of the writer is with the method by bridle between poles, from which are taken equidistant pull offs. It is of course desirable to maintain this backbone dead, but on light curves the weight of the insulators is apt to cause sags which may prove troublesome. This can be helped by placing the insulators at the bridle, in which case of course the pull off itself is alive. In at least one instance the pull-off, of a single piece of seven strand steel rope, was unlayed for the proper distance, three strands going to the messenger, three to the trolley, while the seventh, whipped on the main portion, prevented further unlaying.

There seems to be little actual knowledge as to the comparative values of various types of catenary detail. In the matter of brackets the author expresses a preference for the three part pole collar as the method of attaching the over support rod to the pole. This is a point needing further investigation. The practice of passing the over support rod through a hole in the pole offers opportunity for decay to start, and weakens the pole slightly; on the other hand it has been the writer's experience that the pole collar, unless crushed into the pole, with consequent liability to decay troubles, is apt to slip and lower the end of the bracket. The connection at the bracket end of the over support should also be positive; collars held by a set screw are prone to work loose and make trouble. As to bracket bar, the compound types offer greater attachment facilities, but are presumably more subject to corrosion. Devices at the pole end which permit lateral swing in case of unbalanced pull in the trolley save the bracket in case of heavy strain, as in the case of a broken wire, but the overhead is seriously slacked off for a number of poles each way; with rigid pole connection the brackets nearest the break are apt to be badly crippled if not ruined, but the area of disturbance is much less, a factor of great operating importance. The forms which split and take the pole between the members will stand very severe punishment from a trolley pole that has jumped the wire; socket pole connections, unless pinned or otherwise secured, are very apt to be shaken apart or broken under the same conditions.

As pointed out by the author, the matter of proper tension in the wire is complicated by the fact that conditions preventing excessive sag at high temperature result in very high stresses at low temperatures. How closely these stresses may approach the actual breaking strength of the wire is not always realized. Grooved 4/0 copper trolley is usually credited by the handbooks with a breaking strength of from 8000 to 8400 lb. A series of tests made by the writer, however on commercial stock samples gave a maximum of barely 7100 lb. on the unbrazed portion, with an average at brazes of 5600 lb., two samples failing below 5000 lb. (see Transactions, American Society of Civil Engineers Volume LX page 552).

While there are some differences as to detail commercial trolley wire is in general made from a "wire bar" of rectangular section, which is first rolled down to a round rod and then is finished by drawing. Brazing usually is done just before drawing, and in the samples tested it was evident that the latter treatment was not sufficient to overcome the local annealing at the surfaces of the braze.

The tension is properly dependent upon the nature of the overhead. If hangers are rigid the line between should be given equivalent vertical stiffness either by the form of cross section or by the tension; if hangers are yielding a much lower stress is permissible.

To secure an automatic adjustment the first Syracuse, Lake Shore, and Northern catenary had in the $\frac{7}{16}$-inch stranded steel messenger, at 20 deg. fahr. and for the standard span of three hundred feet, a sag of sixty-eight inches, but the trolley was a foot higher at the center of span than at the supporting bridges (see Transactions, American Society of Civil Engineers, Volume LX page 547). It was hoped this would minimize temperature troubles, but in the writers estimation its chief virtue lay in the fact that it materially stiffened the system against lateral sway. Later installations on this and allied lines have omitted this feature.

It is generally believed by users, that trolley wire could with advantage receive further treatment than is at present usual, for the market material of to-day certainly has decidedly less resistance to wear than the earlier output.

The writer is watching a working test of especially rolled wire which gives to 4/0 grooved copper an average breaking strength of practically 9000 lbs., but there has not elapsed sufficient time to permit any comment of value. The manufacturers, so far as the writer knows, have as yet set no commercial price on the treatment. Mr. T. H. Mather of the Syracuse Lake Shore, and Northern has for some time employed a wire which receives extra finishing treatment. The additional cost was, some time ago, about 6 per cent of the price of untreated wire; at that time Mr. Mather considered the resultant economy in maintenance and repair to be several times that figure.

But it is after all an illogical proceeding to impose the duty of resisting the abrasive action of the collector upon that member of the overhead which by nature is least adapted to resist wear, and functionally is most affected by loss of section, as is the case when the trolley wire is of copper. Phono electric and one or two other bronzes have for some time been used at points of unusually heavy wear, but the employment throughout of a trolley wire designed primarily to resist wear, as in the case of the Denver and Interurban's phono electric, and the New Haven's steel, is of very recent date. The author will doubtless be interested to know that his suggestion of a steel trolley and copper messenger has actually been in service for over a year. The trolley wire is identical in section with 4/0 grooved copper; the messenger is 19 strand bare copper wire cable sagged 24 inches for standard spans of 150 feet. This is on the experimental catenary section of the Connecticut Company's Hartford-Middletown line and the steel wire is continued for about half a mile beyond the catenary in simple suspension. At night the wheel has a bright tail of light but the actual wear in over a year's service is inappreciable, and this is also true of the messenger where it was feared the loops of the sliding hangers might cut the copper. This latter would indicate less danger to galvanizing on a steel messenger from sliding hangers than has been anticipated by some.

The Connecticut Company's experimental catenary has not had long enough service for final deductions as to the most desirable type of hangers, but indications to date seem to point to the old mechanical screw clamp ear with light hanger rod rigidly fastened to the ear, and looped over the messenger. The screws should be long enough to head up after the trolley is gripped; if this is properly done the type is at least as efficient as the more elaborate forms, and is far simpler. In this connection the author expresses a preference for "a nut screwing down on the lower end of the hanger rod, as in figure 24 as it can then never work off". In the writer's experience, while the nut cannot escape, it has been found necessary for such types of hangers to be fitted with a locknut, as otherwise the main nut backs up to the rod enough to loosen the clamp and permit serious wear.

Rigid hangers require high trolley tension, and in case of relative movement of trolley and messenger are apt to come to grief; hinged types if jointed top and bottom and rigidly gripped to messenger allow relative movement and give a little flexibility that hardly seems commensurate with the complication. Bottom slide hangers seem unduly subject to wear, but have the marked advantage that the parts lifted are all of equal weight. The foreign sliding hanger lines have a secondary messenger of very slight sag and the loop hangers are all of equal length and weight; that satisfactory results were not obtained on certain American lines where hangers varied in length from four to twenty inches is hardly surprising. Long loop-hangers hinged at the ear have a tendency to tip when lifted, and sliding down the messenger lose their characteristic feature, and as a result of the shortened effective length, pick up the trolley.

Hangers with jaws closing symmetrically with reference to the rod will, within the limits of their capacity, take various wire sizes equally well; hangers in which the jaws do not so move however, while they have a small range, do not work well on sizes other than the one for which they were designed. For shoe work the contour of the jaws is of less importance; for wheel work it is essential that the jaws give good clearance lines, or, particularly on curves they will be badly pounded.

The matter of hanger spacing is one on which is needed much practical information—in fact this need of much practical information is characteristic of the entire subject of overhead construction. On a forty-mile-per-hour installation for wheel operation, with main spans of one hundred and fifty feet, excellent results are being had with a secondary spacing of ten feet, and barely twenty miles away equally good results are obtained on an installation identical except that the secondary spacing is fifty feet. It is the general impression that for shoe work the secondary spans should be very short; the writer knows of no installation on which long secondaries have actually been tried out, but it would seem that the manifest economy, if the number of hangers can be materially reduced without impairing the efficiency, warrants careful investigation.

The author touches a point of great importance in construction in the matter of hanger rod lengths for various spans. Theoretically the sag of each span should be mathematically exact; practically unavoidable variations occur to an extent which warrants the small amount of "fudging" which may be necessary to adopt standard span hangers to the shorter spans. The importance of reducing to a minimum the labor and the chance of error on the tower cars is best appreciated after a practical experience. In electrifying an operating steam road the work trains lose from fifty to seventy-five per cent of their actual time, the lower figure being reached only under very favorable conditions; with much traffic on the line the time lost dodging trains may easily exceed the seventy-five per cent.

The author's point that strain insulators should under mechanical and electrical stress at the same time, is well taken, particularly where the strains are of the compression type where movement of the parts which in no ways affects the mechanical strength—in some cases actually increase it, due to better seating of parts—may completely destroy the insulating properties.

The difficulty of securing good strain insulators for high voltage work makes desirable the suspended bracket construction similar to that on the Rochester Terminal, and which employs a standard line insulator, in spite of the fact that its weight and area are decided draw backs, particularly in sections subject to sleet.

The author's hope that further investigations will be made in regard to roller types of collar will be shared by all who have investigated the subject and it is by no means impossible that a modification of the present form of trolley wheel may be of much value. The writer has for some time had in mind a shoe design in which the main pantagraph movement ranging through several feet should be effected by some positive mechanical device, probably a pneumatic cylinder, the air supply to be controlled by a sensitive contactor mounted on the main pantagraph. This contactor, having little inertia and therefore able to follow the wire almost instantly, would take care of variations within its range of about one foot each side of the middle point. The valves operating the main traversing device would open as soon as the contactor passed this mid point, and in most instances the response would be sufficiently rapid to keep the movements of the contactor within its limits. If, however, the depression or raise of the wire was so rapid that the main device did not attain the speed at which the change was occurring before the contactor reached its outer limit the conditions would be no different from those which at present obtain a very material portion of the time; on too rapid raise there would be an actual break in the contact; on too rapid depression the main traverse would be forced down by the overhead until its acceleration was equal to the rate of drop in the line.

Ralph D. Mershon: The author says that porcelain "can be moulded and worked into almost any desired form or size" This does not agree with my experience. I have designed insulators from time to time and endeavored to have them made out of porcelain. In some cases I have succeeded in having them made, and in some I have not. Not infrequently, where I did succeed, the price was prohibitive. As the result of the experience gained from such work in connection with a number of the insulator manufacturers of this country, I should say that porcelain, for insulators at least, can be practically moulded and worked into very few forms of limited size. The present practical limit in thickness of porcelain of high dielectric strength is about ⅝ in. In some cases it is possible to get thicknesses of ¾ in. of high dielectric strength, but such pieces are usually produced at very considerable expense, and their production is uncertain.

The author's investigations of the physical properties of porcelain are interesting, but might, with advantage, have been carried a good deal further. The procelain he tested could hardly have been of the best quality as regards mechanical strength. The highest grade high-voltage porcelain made in this country will show a tensile strength of from 1,500 to 2,000 lb. per sq. in and a compressive strength of approximately ten times this. These figures are the result of a great many tests made by myself and by others.

Of course, ceramic materials of all degrees of strength less than this are met with, but it is also possible to obtain material of greater strength. I have tested ceramic material which ran as high as 2,400 lb. per sq. in. As it happened, however, this material was not the highest grade high-voltage porcelain. It was not vitrified throughout, if it was vitrified at all. The fracture showed fissures, and in general its appearance was such as to lead one to think it would have a very low tensile strength.

There is a great deal of work to be done yet in connection with ceramic materials for electrical work, and undoubtedly room for great improvement. It is extremely desirable to determine the conditions which affect the mechanical strength of such material, especially the tensile strength. Some investigations I have made seem to indicate that it is possible for porcelain to have a grain, something almost of the nature of a fibre, such as we find in wood or wrought iron.

A great deal depends, with different mixes, upon the amount of moisture present when the piece is formed, and whether the piece be formed by pressing or by the plastic method. It would appear, also, that, with some porcelain mixes at least, the degree of firing has a great deal to do with the strength. In some cases it would appear that a temperature considerably below that at which the mixture will vitrify, or even begin to vitrify, will result in greater tensile strength than if the heat be carried higher.

My investigations have been confined to American porcelains. Apparently some of the European porcelains run a great deal higher in mechanical strength. In the discussion of a paper recently presented before the Institution of Electrical Engineers at Manchester, England, Professor A. Schwarz gives the results of some tests he made upon porcelain. The tensile strength ran from 3,316 lb. per sq. in., for a rectangular test piece with a section of 0.2 sq. in., down to about 2000 lb. per sq. in., for a rectangular piece of 0.6 sq. in. in section. He found a compressive strength of 10,000 lb. per sq. in., for a cylinder two in. long by two in. in diameter; 40,000 lb. per sq. in. for a cylinder one in. in diameter, and 52,600 lb. per sq. in. for a cylinder $\frac{7}{16}$ in. in diameter. He ascribes the lesser strength in the larger pieces to lack of heat penetration in firing, but I think it not unlikely that the apparent fibrous structure mentioned above had also a considerable amount of influence, especially if the cylinders were formed from plastic clay. It is evident that with such formation, the smaller the cylinder, the greater the proportion of its bulk that will partake of a fibrous structure.

In this matter of comparing strengths of different samples of porcelain, we, in our present ignorance, assume that all porcelain is alike. Such comparisons are about as logical as to compare tests made on high grade steel and tests made on the poorest quality of cast iron. Until this whole subject is given a more thorough study, we shall have no intelligent basis on which to compare results obtained at different times and with materials obtained from different sources.

O. S. Lyford, Jr.: The ideal conductor for the distribution of electric power for heavy railway operation is one that is either absolutely flexible or absolutely rigid, and parallel to the running rails. For low voltage work, which in heavy service involves the collection of large currents, the tendency is towards the rigid conductor, as characterized by the third rail. For high voltage work and consequent low current the tendency is towards absolute flexibility of structure and catenary trolley construction has been the best development thus far. Improvements in third rail construction have been in the direction of greater rigidity and improvements in catenary construction towards greater flexibility.

For intermediate voltages, it remains to be seen what construction will prevail and neither of these two, as now developed, is entirely suitable. For instance in the 1200 volt direct current system the currents are high for heavy railway operation. A locomotive such as recently adopted by one of the large railroads with motors capable of developing 4,000 h.p. in starting, the maximum current at 1200 volts would be 2800 amperes and the running current for maximum weight of train 1250 amperes. A suitable conductor for distribution of current to such locomotives must necessarily be heavy and the logical development is in the direction of rigidity of construction. This means either the perfection of a safe 1200 volt insulation for third rail or the development of a rigid overhead structure. The latter will necessarily be a very heavy and expensive construction and one open to many objections from the point of view of railway operation and maintenance. The former is possible, and is already being tried out, but if designed for usual railway clearances it will necessarily be cramped.

The two papers presented to-night relate to materials and apparatus for light structures with moderate stresses and therefore apply more particularly to constructions approaching absolute flexibility. The discussion should be considered from that point of view.

Referring first to Mr. Kempton's paper, the tests reported verify the conclusion that porcelain used in compression is suitable for such strains as are likely to occur with a flexible and comparatively light overhead system. Referring to the question raised in the paper as to whether mechanical stresses weaken the porcelain stock electrically and therefore whether the combined mechanical and electrical test is necessary, it is the writer's belief that Mr. Kempton has arrived at the answer in the following statement:

> "It was thought probable that the high stress in the section of porcelain under the load opened up slight flaws in the stock, rather than causing the sound porcelain to puncture below its unstrained puncture voltage."

It is possible that if the compression were applied to the insulator stock in such a manner as to absolutely distribute the pressure uniformly, there would be no evidence that a mechanical stress within the breaking limit weakened the insulator electrically. As a matter of fact, insulators of the style illustrated by Fig. 9 of Mr. Kempton's paper are subjected to a fairly uniform and not very heavy unit stress, this being in tension.

With the various forms of insulators for use in compression, however, the stress is not distributed uniformly, as the metal parts are are necessarily elastic. For instance, in the double spool strain insulator illustrated by Fig. 29 of Mr. Smith's paper, there is necessarily some irregularity in the application of the mechanical stress to the porcelain. This difficulty also exists with the "loop" or "fish-tail" type of insulators. It was in the testing of these two types of strain insulators that we found it necessary to apply mechanical and electrical stresses simultaneously to determine the true safe limits of the insulator. It is the writers belief that after sufficient experience with a strain insulator of a given form it will not be necessary to make the combined tests on every insulator, but in this catenary work for heavy electric traction, which will usually have to be erected over a line already in operation, any reasonable expense in testing which will avoid replacement of insulators in the completed structure will ordinarily be found justifiable.

Referring to Mr. Smith's paper, the following comments are offered.

Poles and Bridges. There is still room for the development of a light form of pole to take the place of wood. One of the principal criticisms which maintenance-of-way officials make to the electrification with overhead trolley system is the danger to persons and property in the case of a derailment or collision which may result in overthrowing the overhead structure. It has been found that with wooden poles supporting a strong catenary structure, a derailment will result in cutting away the pole without bringing down the conductors. Heavy bridge work or heavy steel pole structures will not act as satisfactorily in such accidents.

Messenger and Trolley Wires. Mr. Smith refers to the use of a dynamometer in the rection of the messenger and trolley wires. Such practice was at first viewed with scorn by the superintendent who handled the Denver & Interurban work, and he has had very extensive experience in the construction of trolley work and transmission lines. Before the job was completed, however, this superintendent was enthusiastic over the results obtained, as he found time was actually saved and the structure when complete required very little readjustment and this only during construction and not after operation was begun. Since we left the job it has not been necessary to take out any slack or make material readjustments. This seems to prove also that the tension used, namely from 2000 to 5000 pounds, depending on the temperature, is entirely practicable and produces good results.

Use of Tension Devices for Trolley Wire. There was a question in the writer's mind as to whether the success of these devices in Europe was not due to the fact that the current collector used is very light and flexible. Such collectors are practicable in Europe where train speeds are relatively low, the variations in height of trolley are relatively small and currents collected are relatively low compared to American practice, but with the service which we are called upon to operate in this country such forms of pantagraph have thus far proved impracticable. With the American form of pantagraph shoe a pressure of at least 14 lb. seems to be necessary. Such shoes were tested out on the Pennsylvania R.R. test track and the writer watched their operation closely on the German form of catenary and compared this operation with operation on German roads previously inspected. The results, in so far as they could be noted with the brief tests on the short section of track, indicated that the American form of shoe will work as well as the European form, although this is quite contrary to the expectation of European engineers. It is the writer's belief that the success of this combination will depend on the ability to eliminate hard spots from the line. This seems possible at practically all points where high speeds are necessary.

Referring to Mr. Coomb's report that in the Pennsylvania R.R. test a form of catenary construction with one messenger and one conducting wire, the latter being supported with thin flexible hangers, gave as good results as operation on the German type of construction—this presumably relates to the action of the pantagraph shoe on the two types of conductor support, and seems reasonable to expect, as the flexibility of the simple construction is practically a great as that of the German construction provided there is sufficient distance between the messenger and the trolley wire so that the hangers are at all points long enough to be flexible. One question in relation to such a construction can be determined only by a test extending over a considerable time. This is the life of the flexible hangers. The oldest catenary trolley road in operation is that of the Stubaitalbahn at Insbruch. On this line a simple catenary is used and the hangers are of galvanized iron wire, apparently about No. 12 in size. The writer inspected this line about two years ago and noted that many of these hangers were broken, apparently due to the vibration of the trolley wire. Such breakage will not occur with the heavier forms of trolley hangers described in Mr. Smith's paper.

Referring to the European construction mentioned by Mr. Smith, it is the writer's understanding that this construction was developed by the Allgemeine Electricitats Gasellshaft to obviate the necessity of tension devices used in the Siemens-Schuckert construction. It was believed with the use of an equalizer such as is illustrated in Fig. 16, the expansions and contractions in a catenary structure due to changes of temperature would be taken care of satisfactorily, without any other adjustment.

Catenary Hangers. Referring to the various forms of catenary hanger illustrated, one point which should be looked out for is that the hangers shall not damage the galvanizing of the messenger cable. This cable is an expensive item of the catenary structure and one hard to replace without delay to the traffic. It is therefore important that the life of the cable shall be as long as possible and to this end the galvanizing should remain intact. A form of hanger which has a flat loop over the messenger wire is therefore safer than a sister hook construction or any other form in which the cable may be more or less cramped. As Mr. Thurston pointed out, the design of the loop over the messenger should be such that the hanger can be moved along the messenger easily.

Steady Strain Device. Referring to the device illustrated in Fig. 28, of Mr Smith's paper, attention is called to the fact that the brace between the trolley wire and insulator is so short that without material change in the length of the bracket it is possible to place the steady strain insulator on either side of the main insulator and therefore always have the steady strain in tension. On other words, it is not necessary to use the steady strain as a strut which may produce a hard spot, as suggested by one of the speakers.

Strain Insulators. Mr. Smith makes a very good point regarding the disc type of insulator as follows:

> "An excellent point about the disc type of insulator when used within its capacity is that there is a mechanical linkage of the guy cables on opposite sides of it, which prevents their falling apart if the porcelain breaks."

This feature should be incorporated in all strain insulator construction. It exists in the double spool strain insulator illustrated in Fig. 29 of Mr. Smith's paper. It cannot, however, be incorporated in such wood strain insulators as now employed and this is one of the principal objections to the use of wood, as either burning or breaking of the wood will throw the overhead structure out of alignment and possibly drop it.

W. H. Kempton: In speaking of porcelain and its quality, I do not want to give the impression that I do not have faith in it, but rather that I realize its limitations. All companies making high-voltage insulators, have developed the material to such a point that it is quite reliable; and while there is still room for improvement in porcelain insulators, and while many companies are trying to improve their quality and get more uniform results, still I think it is well to admit just how reliable porcelain is, and use that information in our designs. In that way we will avoid over-confidence, and thus get a design which will not break down in service.

Regarding Fig. 9 of the paper, I regret that I did not fully explain in the original paper that this is not a commercial insulator. It was made for the deliberate purpose of getting what Mr. Thomas points out; a pure tension stress for the purpose of a combined mechanical and electrical test.

As a matter of fact, the company with which I am connected manufactures large quantities of insulators along the line Mr. Thomas suggested: that is with the pin extended far up into the head and cemented in. We have made them with a mechanical strength of over 15,000 lb. That form was not touched on in this paper, as it is used as a suspension insulator. I did not expect to include that form of insulator in the discussion, and so avoided bringing the matter up.

Referring to the other question, regarding the protection of the insulator, I personally am convinced that the breaking of the petticoats on the insulators he described, was not due directly to electrical stresses. I have punctured many insulators and have yet to find one that broke, except under mechanical strain, or due to the heat from the arc. It is possible in the instance he described, that it was first punctured, and the heat from the following arc concentrated on that spot on the insulator, caused it to burst.

Another explanation might be added although it is rather far-fetched, and I do not think is correct; that is, that type of insulator has considerable capacity, and due to the high frequency of the lightning, it is possible there would be a marked vibration of the porcelain. But I do not think it possible to get sufficient vibration to shatter the porcelain.

The large disks of porcelain, as now manufactured, are pretty tough and I think it was the heat from the arc in the case cited, that broke the insulator. I have had them fail in a very similar manner in actual tests.

Assuming however that the insulators were broken directly by stresses due to the lightning, a remedy would be the use of suspension insulators made up of a number of units. One or more of these units might be broken without disabling the line, but I do not think it possible for all of them to be broken in that way.

The accompanying cut shows a suspension insulator made up of eight units. Of course, the insulator may be made up of the proper number of units to suit the voltage of the line. Each of these units is ten inches in diameter and has dry flash-over voltage of 90,000 volts.

Replying to Mr. Mershon's comments, I think his statements in a measure verify my claims. As pointed out in my paper, the samples used were made without any attempt to secure extra good quality. The figures given are such that they may be used for design work with safety. As pointed out, especially prepared samples can be made with the same mixture and carefully burned and much higher results be obtained. Such samples are always made with uniform section and comparatively small. I have made tests with very much higher results, but did not give these figures for the reason that if they were used in a design, the insulator would fail to come up to the expectations of the engineer, and the manufacturer would be discredited as also would porcelain as an insulating material having mechanical strength.

Bronze is a parallel case. Government experiments show that bronze can be made with a tensile strength of 100,000 pounds per sq. in. and over, but practical foundrymen will decline to guarantee over 50,000 lb. to 60,000 lb. per sq. in.

It would be interesting to know if the dielectric strength of the samples made by Professor Schwarz was as good as the best American product. The two qualities must be worked out together. High tensile strength can be had at the expense of dielectric strength.

Mr. Mershon's criticism of my statement regarding the range of porcelain manufacture is in a measure merited. When it is considered that high voltage material must be moulded in a plastic state, dried, and then burned at a temperature that renders it pliable, it will be seen that it is difficult to make beyond a certain size and that the shape must facilltate moulding and drying the clay.

Referring to the " grain " noted by Mr. Mershon, it might be said that it is practically impossible to mould wet clay into insulator forms without its having a more or less marked fibrous structure. It might also be added that, to the best of the writer's knowledge, it is impossible to make high voltage porcelain by the " dry press " process. In the wet process, the clay is mixed with water to a plastic state when all air can be removed from the body. When the clay dries, it leaves a dense close grained body. In the " dry " process, the clay is ground up dry and made moist enough to make it retain its shape when pressed in a mould. Mechanical pressure is depended upon to make the body compact, and experience has proven that a sufficiently dense body cannot be obtained in this way for high voltage work.

There are one or two points I should like to speak of in connection with Mr. Smith's paper: one is in regard to the length of the brackets for a spacing of eight feet between the center of the track and the center of the pole. From a rather uncomfortable experience, I found it was necessary to use a longer bracket on curves than on tangent, when the poles were placed on the outside of the curve. This is due to the rake of the pole in one direction, and the elevation of the track in the other. With these conditions it is necessary to use extra long brackets on curves, or longer ones everywhere.

Mr. Smith speaks of lining up trolley wires on the curves when pantograph trolleys are used I think it is unwise to allow as much deviation from the center line on curves as was the practice at the beginning There are four considerations to be borne in mind in this connection. One is the rake of the pole; two, the elevation of the outer rail; three, the speed; four, the play of the bolsters on the car.

At standstill or at slow speed on curves the pantagraph trolley tends to swing toward the inside of the curve; but when running round the curve at 40 miles an hour, the momentum of the car throws it over on the bolsters toward the outside of the curve so that there is a difference of from 10 to 12 in. in the position of the trolley with respect to the wire. In one case, the line had been constructed very carefully; but in spite of that the pantagraph trolley would swing out free from the trolley wire and pull down some of the line or pull the trolley from the car. It looked impossible from measurements on the line until we discovered that the construction of the car allowed it to swing over on the bolsters when going around the curve at high speed, sufficient to throw the pantagraph clear of the trolley wire. The remedy in that case was to re-line-up the trolley wire and add more poles or pull-offs where necessary to reduce the offset of the trolley wire and then fix up the car to avoid such excessive swaying

This is one of the personal experiences I have had emphasizing the care that must be exercised in the erecting of a trolley line on which pantagraph trolleys are to be used.

W. N. Smith: The remarks of those who have joined in the discussion quite generally agree as to the fundamental principles underlying catenary construction.

As was stated by the Chairman, the overhead line still offers a great number of unsolved problems. Fortunately they are of a type capable of being attacked by the profession at large. Comparatively few electrical railway engineers have been trained as designers in electrical factories, and those who have not can hardly approach the problems of motor design at the point where the most of our alternating current railway discussions begin. Intricate theories of motor design require a mathematical ability which is not so well distributed amongst engineers generally as is the plain good sense which must underlie the planning and execution of every large undertaking in railway electrification. Problems of overhead construction, and of the equipment related thereto, are mostly mechanical, and are thus open for solution to engineers generally on a broader and more liberal basis than is usually embraced in the commercial or manufacturing point of view—as has been indicated this evening.

Taking up the various comments in their order, it seems to me that Mr. Coombs answered Mr. Thomas's question in respect to the secondary arm or tip which has sometimes been employed at the top of the main pantagraph. This device has been used on the Simplon tunnel locomotives with sliding shoe on the tip. The Simplon locomotives travel with a maximum speed of 45 miles per hour and the contact shoes are of the sliding type. Even with the lessened inertia of this device, the shoes only last about 1700 miles.

It is true that my references to the beginnings of catenary construction applied only to its use in this country, as there has not been very much evidence that at the time of its introduction in America, our practice was influenced particularly by European methods.

Mr. Hixon's reference to wave action brings out a fundamental principle underlying successful catenary construction and operation where circumstances are favorable; that is to say, I believe that the best results will be obtained when wave action, as referred to by Mr. Hixon, is recognized and provided for. This depends very largely on the construction of hanger employed, and only experience can demonstrate which type of yielding or floating trolley hanger is really the best. The experiments mentioned by Mr. Hixon and Mr. Harte will doubtless help in determining this exceedingly important matter.

The fact that the old pole and wheel trolley operates so well with trolley wires having considerable sag, illustrates the importance of recognizing wave action, which is so much in evidence with the wheel type trolley; and this confirms my belief that the natural and desirable wave action in the trolley wire will be very much helped by the roller pantograph, and with less wear and tear than with the sliding pantograph. This point of view is based upon the probability that the heavy work of the future will be at high tensions, *i. e.*, at 11,000 volts or higher, and that the trolley pole and the narrow grooved wheel accompanying it will not be regarded as thoroughly reliable for high speed operation under steam railroad conditions, so that it will be necessary to have a transverse rolling or sliding contact which will not leave the wire under any circumstances and which the motorman or the train conductor will not be obliged to regard as an extra source of responsibility or worry. The problem becomes then one of flexible operation at high speed with a transverse contact device, and it is quite evident that the successful operation of such a combination will be met only by recognizing and providing for a vertical wave action in the trolley line.

Mr. Coombs reminds us of the fact, commonly overlooked that the railroad track itself is not a plane surface as it is usually considered to be, and that the train itself makes a wave action in the rails as it runs over the track. This emphasizes the necessity for directing our efforts towards upward flexibility in the trolley wire, rather than to smoothness without flexibility.

With respect to the possible twisting in the compound catenary construction, illustrated in Fig. 27, as apprehended by Mr. Coombs; it would seem to me that where the wires are strung to a fairly even tension, and the hangers of the proper length, and all parts securely and tightly drawn up, there would not be any tendency to roll when the line is properly adjusted. If one of the wires is much tighter than the other there will, of course, be a tendency for the structure to get out of position.

I agree with Mr. Thurston that it is very desirable to have the connection at the top of the spacing rod flexible, so as to allow it to move with reference to the messenger wire. This is an instance of the value of practical experience—in showing the value of flexibility, which engineers were chary of a few years ago.

Mr. Harte emphasized the interesting fact that successful operation depends on uniformity of resistance at the contact surface, *i.e.*, hard spots should be kept out of a yielding line or soft spots out of a hard line, or, in other words, the line should be either uniformly hard or uniformly yielding. The successful operation of the Denver & Interurban catenary line has been due to the fact that it was uniformly hard and smooth, and the reason why it was built in that manner was, in the first place, because it was necessary to use the sliding pantograph bow, the wheel trolley being regarded as impracticable; secondly, we had to make use of such types of hangers as were commercially available at the time, there being no flexible type hangers of known reliability then manufactured; consequently it was impossible to construct a line which we could be sure would be uniformly flexible, and we were therefore obliged to adopt the method of making the line uniformly hard and smooth, which was done in the manner indicated in the paper, and which has proved to be successful as a working proposition. Having no means for making the line flexible, we did the next best thing; and while I will readily admit that it would in some respects have been an easier line to build if it had not been necessary to draw it so tight, two years of operation and maintenance have developed no defects, and apparently it is as satisfactory to operate as though it were of the flexible type.

The experimental lines constructed with flexible hangers mentioned by Mr. Hixon and Mr. Harte will doubtless have considerable effect in determining the development of catenary details, but it now appears that both the Schenectady and Connecticut lines are operating with wheel trolleys and not with sliding bows. It seems to me that the contact-making conditions which must be ultimately fulfilled by equipment for heavy traction are not being met in these installations, and to that extent they will be somewhat inconclusive. If they should be tried out with pantagraph trolleys of the sliding or roller type, then there would be something definite upon which to base conclusions for the heavy and high speed work of the future.

The question of clearance referred to by Mr. Kempton, is, of course, one that pertains to conditions on each particular job; 8 feet was mentioned as a minimum which was actually used in a large installation without any bad results. I believe, however, that 8½ feet is better, as used on the Denver & Interurban line.

The inclination of the trolley brackets on curves was varied from the horizontal; if car leaned away from the pole, the bracket is inclined downwards; if toward the pole, the bracket is inclined upwards, in order to prevent the horizontal pantograph bar from fouling the bracket arm.

The roller type of trolley contact has been in use in Europe for some years; the Valtellina installation in Italy being perhaps the best known instance of its application there. I referred to its use on the Pacific coast as the first and only application of its use in this country. Since writing the paper I have ascertained through the *Electric Journal* that on the Valtellina line, where the overhead construction is not very tight (and not of the catenary type) the rollers have an average life of 15,500 miles and frequently carry more than 200 amperes per roller, and that in the opinion of Mr. Von Kando of the Italian Westinghouse Co. the excellent life of the contact roller is due partly to the difference between rolling and sliding friction, and partly to the fact that each element of the roller is heated by the passing current only at the instant of contact, and does not remain in contact long enough to get melted; while with the sliding contact the wear is excessive when the current is more than 50 amperes.

It seems to be agreed that the vertical flexible working conductor is very desirable, and the best reports of smooth operation with it emanate from installations where the rolling and not the sliding contact is used.

It is my belief that trolley pole and wheel are not suitable for heavy railroad operation at high tensions and speeds, and that the horizontal transverse form of contact device is indispensable under such conditions; and I suggest that the next step forward should be in the development of the roller type of contact against the yielding or floating trolley wire, in which the elements of wire tension, contact pressure, and pantograph inertia will be compromised to produce the desired effect.

It has been stated by men who have had good opportunities for actual observation, that when speeds of 45 miles per hour or so are exceeded, the conditions to be met by an overhead contact device for heavy currents are so difficult as to be beyond the field of experience at lower speeds. Granting this to be true, there is all the more reason for developing practical mechanical devices for making contact. Only experiment can decide the question positively, and it remains to be seen whether the devices above suggested can be adapted to high speed, or whether recourse must be had to some combination yet to be invented.

Edwin B. Katte (by letter): The following is a description of porcelain strain insulators used upon a recently constructed 11,000-volt aerial transmission line and a 650-volt direct current distribution system.

Specifications. The 11,000-volt strain insulators shall be of two piece construction; the 650-volt strain insulators shall be a single piece of porcelain. Porcelain surfaces shall be thoroughly glazed a uniform brown color, shall be free from pits, cracks or other imperfections and the material sound and homogeneous throughout. All insulators shall conform to the dimensions given on the attached illustration, Fig. 1 and Fig. 2, within 3/32 in. except those given for pin holes which shall conform to the drawing to within 1/16 in.

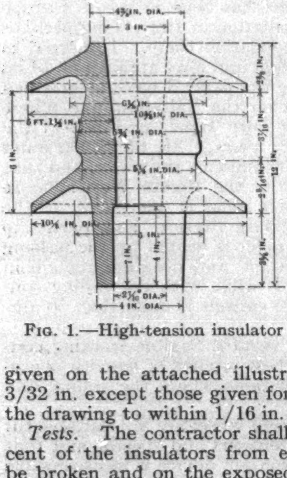
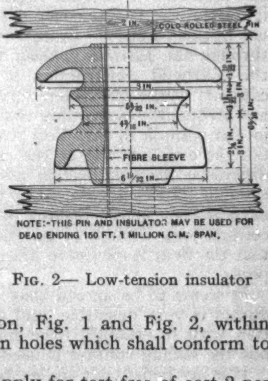


Fig. 1.—High-tension insulator



NOTE:-THIS PIN AND INSULATOR MAY BE USED FOR DEAD ENDING 150 FT. 1 MILLION C. M. SPAN.

Fig. 2— Low-tension insulator

Tests. The contractor shall supply for test free of cost 2 per cent of the insulators from each furnace charge. These shall be broken and on the exposed surface shall be placed drops of red ink which shall not spread or show signs of absorption. The exposed surface shall be free from cracks, checks, blow-holes, etc., and shall show a close and uniform grain.

A. *High Tension Strain Insulators*. Each 11,000-volt strain insulator selected by the inspector shall be mounted on a two-in. metal pin, shall be subjected to a potential of 80,000 volts applied between the pin and the wire groove for one minute without showing signs of breakdown, leakage or excessive brush discharges. When mounted in a vertical position on a 2-in. metal pin and subjected to a precipitation of ¾ in. of clear water per minute with current applied between pin and wire groove the insulators shall not break down or arc over at less than 50,000 volts. Each insulator when mounted upon a steel bar in a manner to be approved by the engineer shall safely withstand a continuous load perpendicular to the pin of 9,000 lb. applied by means of a No. 4/0 seven-strand, hard-drawn copper cable.

B. *Low Tension Strain Insulators*. Each 650-volt strain insulator selected by the inspector shall be mounted on a 2-inch metal pin, shall be subjected to a potential of 30,000 volts applied between the pin and the wire groove for one minute without showing indications of conductivity, breakdown or surface leakage. When mounted in a vertical position on a 2-inch metal pin and subjected to a precipitation of ¾ of an inch of clear water per minute with current applied between pin and wire groove the insulator shall not break down or arc over at less than 16,000 volts. Each insulator when mounted upon a steel bar in a manner to be approved by the engineer shall safely withstand a continuous load perpendicular to the pin of 10,000 lb. applied by means of a 1,000,000 circular mill, 91-strand, hard-drawn copper cable. Each insulator shall withstand, momentarily, without sign of fracture, 15,000 lb. applied in the manner specified.

SUMMARY OF TESTS

Type of insulator	Electrical requirements
11,000-volt strain	Dry, 80,000 volts for one minute. Wet, 50,000 volts without arcing.
650-volt strain	Dry, 30,000 volts for one minute. Wet, 16,000 volts without arcing.
	Mechanical requirements
11,000-volt strain	Continuous load of 9,000 lb.
650-volt strain	Continuous load of 10,000 lb.
650-volt strain	Momentarily load of 15,000 lb.

Inspection Results. Competitive bids were invited for high and low tension strain insulators and the contract finally awarded to an insulator manufacturer of high standing. Insulators were offered for inspection and acceptance with the following results:

Type of insulator	Total No. delivered	Number accepted	Per cent rejected
11,000-volt strain	156	129	17.3
650-volt strain	172	163	5.2

Mechanical Tests. From a large number of tests to determine the mechanical strength of the insulators the following have been selected as typical:

11,000 VOLT STRAIN INSULATORS

No. of test	Pounds pressure	Time pressure applied	Remarks
13	11,390	5 mins.	O. K.
13	13,400	3 mins.	Cracks developed.
13	13,735	Instantly	Failure.
14	8040	10 mins.	O. K.
14	10 720	2 mins.	Cracks developed.
14	11,055	Instantly.	Failure.

650 VOLT STRAIN INSULATORS

11	6,700	5 mins.	O. K.
11	10,050	3 mins.	O. K.
11	10,385	Instantly	Failure.
12	8,710	3 mins.	O. K.
12	12,060	2 mins.	O. K.
12	13,400	Instantly.	Failure.

Results in Service. The insulators described above have been in continuous service for about three years with the following results.

Type of insulator	No. installed	Mech. failures	Elec. failures	Broken by violence	Per cent Failure from all causes
High tension strain............	101	5	0	0	4.9
Low tension strain.............	86	8	0	0	9.4

Conclusions. It must be concluded from the above that the per cent of mechanical failures has been high considering the care with which the original shipments were inspected and tested. For the relatively low voltages there is no difficulty in securing the requisite electrical strength, but further combined efforts of engineers and manufacturers are necessary to secure greater mechanical strength in porcelain strain insulators for heavy service.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 28, 1910.

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CONSERVATION OF WATER POWERS

PRESIDENTS ADDRESS

BY LEWIS B. STILLWELL.

The conference of governors, which assembled at the White House, in May, 1908, in response to an invitation extended by President Roosevelt, focused the attention of the American people upon a subject which all recognize as one of fundamental national importance and one which appeals to the engineering profession with all the force which comes from special knowledge. True conservation of our natural resources means wise utilization of those resources without unnecessary waste. Such utilization of materials used in construction and of energy is the primary and essential business of the engineer. Since the days of Smeaton and of Watt, the engineer has been building the lighthouses of material prosperity and releasing and directing for the common welfare, those vast forces of nature imprisoned and overlooked for centuries but now utilized on a scale which dwarfs the physical powers of man to insignificance.

During the last 25 years, a period practically coterminus with the life of this Institute to date, the art of transmitting power by electricity has grown from a laboratory experiment into a development universally recognized as one of the great factors of industrial and commercial life.

The latest publication of the United States Geological Survey, relative to this subject, estimates the aggregate water powers of the United States at minimum flow to be 36,000,000 horse power and the aggregate which presumably can be developed on the basis of six months' flow per annum at not less than 67,000,000 horse power.

A very large proportion of the water powers hitherto unappropriated are either located upon government lands or are dependent, wholly or in part, upon the run-off from government lands.

The regulations established by national and state governments which control or affect the further utilization of water powers, therefore, are of peculiar concern to the members of this Institute. A bill endorsed by the administration is now before Congress which, if passed, will confer definitely upon the President and his executive assistants full authority in respect of withdrawal of public lands and unappropriated water powers. Probably the bill will pass and if so we may expect that the question of governmental machinery and methods for handling practically this highly complex and vitally important subject will be raised in acute form.

If the views of the engineering profession are to be effective, either in moulding public opinion or in assisting the legislative and executive representatives of our people, by supplying facts essential to correct generalizations and deductions, it is important that those views be clearly stated at the right time and that apparent lack of agreement among those best qualified to measure the practical results of existing or proposed governmental regulations should not destroy their influence.

The present occasion seems opportune for the presentation of a brief and non-technical discussion of the practical bearing and effect of existing laws governing the appropriation of water powers located on public lands, which, as now construed and applied, are seriously retarding the utilization of these powers.

To those who realize the vast possibilities of a far-sighted and thoroughly scientific development and utilization of our water power resources, particularly those of the Rocky Mountains and the Sierras, no subject can be more interesting. Present practice, whether ideal or faulty, is more likely to be modified than revolutionized, and now is the time for unprejudiced and candid discussion of the regulations now in force.

(1) THE RELATION OF FORESTS AND STREAM FLOW

The Bureau of Forestry has established regulations governing the appropriation of water powers located on streams which drain watersheds included in whole or in part in Forest Reserves. Among these regulations is the imposition of a graduated rental, to be paid by the individual or corporation appropriating the water power and used by the government for forest purposes. This rental rests upon the assumption that the appropriator of the power will be benefited by the preservation of the forest, and this idea is accepted generally by engineers and by the public.

Mr. Gifford Pinchot, Chief Forester at the time when the present regulations were established, states his understanding of the physical facts upon which this charge is based in a document explaining the policy of the Forest Service, as follows:

> The National Forests include the great mountain chains of the west. The rain and melting snow of these ranges feed the mountain streams. The forest cover on the steep slopes acts like a mighty sponge, absorbing the excess of rainfall in the wet season and giving it out to the thirsty lands in the dry season. It is for the express purpose of thus 'securing favorable conditions of water flows' (Acts. June 4, 1897) that Congress has authorized the creation of national forests and expends money for their administration and maintenance. Where the forest cover is destroyed by reckless lumbering and the fires which inevitably follow, the rains immediately run off the steep slopes as from the roof of a house, producing destructive floods in the valleys and leaving no store of water for the dry season. Therefore, when a power company puts its plant on national forest land, it gets from the government two things which it ought to pay for, *viz.*, (*a*) The use of lands of great value for power purposes, for the steep mountain sides give the fall which is essential for a power plant; (*b*) the guarantee of a steady flow of water as an incident to the land occupied by the plant. This steady flow is also essential to a power plant.

During the last two years, the question of the actual or assumed effect of forests on the watershed in regulating the run-off, has been widely debated. That forest cover controls the run-off to a material extent has been vigorously asserted by engineers prominent in the government service and by many others, and on the other hand, it has been seriously questioned by a number of our leading engineers, notably by Col. Chittenden, in a paper read before the American Society of Civil Engineers, in March, 1909, and by Dr. Willis L. Moore, Chief of the United States Weather Bureau, in a report addressed to the Committee on Agriculture, of the House of Representatives, in 1910, entitled "A Report on the Influence of Forests on Climate and on Floods."

I do not propose to enter into a detailed discussion of this complex subject at this time. Col. Chittenden's paper and its discussion, as printed in the Transactions of the American Society of Civil Engineers, have covered the subject perhaps substantially as well as it can be covered by applying the inductive method to existing records.

The report of Dr. Moore and the article on "Floods", in Water Supply Paper No. 234, prepared by Marshall O. Leighton, Chief Hydrographer of the U. S. Geological Survey have also debated the subject at great length, the radical difference of opinion between these two gentlemen being due apparently in large degree, to the fact that Dr. Moore is considering total annual run-off, while Mr. Leighton is investigating the relation of "flood tendency" to precipitation.

As Dr. George F. Swain pointed out in a recent discussion of this subject at Boston, the difficulty in reaching an agreement along the lines adopted in the papers referred to results from the fact that all of these gentlemen are applying the inductive method of reasoning to a subject so complex and so varied as practically to preclude the possibility of general agreement in the inferences drawn. The physical laws which govern the phenomena under discussion are all well known, and to the scientist the deductive method of dealing with this subject is not only easier but is more convincing than the attempt to draw conclusions from incomplete records of precipitation and stream flow where even approximate knowledge of the extent to which the surface of the watershed in question is forested, or plowed, or covered by vegetation other than forest, is not available.

Such reasoning unquestionably leads to the conclusion that the preservation of forests on the watershed does to a greater or less extent regulate and control not the aggregate annual run-off but the rate at which that run-off varies during the year, and this idea is accepted generally by engineers and by the public. It is also accepted apparently by the majority of engineers who have discussed this subject in our various engineering publications, using the inductive method in drawing their conclusions.

As the essential physical facts which bear directly upon forest control of run-off, and consequently upon the relation of forested watersheds and water power, the following as stated by Dr. Moore may be accepted probably without material error:

(1) Precipitation controls forestation, but forestation has little or no effect upon precipitation.

(2) Any local modification of temperature and humidity caused by the presence or absence of forest covering the buildings of villages and cities etc., could not extend upward more than a few hundred feet, and in this stratum of air saturation rarely occurs, even during rainfall, whereas precipitation is the result of conditions that exist at such altitudes as not to be controlled or affected by the small thermal irregularities of the surface air.

(3) During the period of accurate observations, the total annual pre-

cipitation has not increased or decreased to an extent worthy of consideration.

(4) The total annual run-off of our rivers is not affected materially by any other factor than precipitation.

(5) There is no adequate evidence to justify the conclusion that extreme floods in recent years attain higher stages than formerly.

Other conclusions stated by Dr. Moore in the report above referred to the author is not prepared to accept, and as regards that forest control which is practically related to the commercial value of water powers, he believes the following to be a correct statement:

While the aggregate annual run-off of our rivers in general depends upon the total annual precipitation, the presence of forest cover on the watershed regulates the rate of run-off to an extent which in many cases materially affects the value of the water power, this regulation tending to equalize the flow and prolong it during the dry season.

With this understanding of the essential physical facts which are pertinent it is proposed in this paper (1) to discuss briefly certain provisions included in the present regulations of the Forest Service governing the appropriation of water powers dependent in whole or in part upon forest reserves, and (2) to suggest the outline of a plan which to the author appears preferable to that now in force.

The present form of permit provides a nominal charge (rental) for the land occupied by power house, dam, canals, penstocks, flumes, etc., the rate being " One dollar per acre and Five dollars per mile for the land occupied by said works ". It provides also that " the gross operation charge for any year shall be calculated by the forester upon the basis of the quantity of electric energy generated in such year at a maximum rate, which shall not exceed the following amounts per thousand kilowatt hours:

For the 1st year	2	cents
" 2nd "	4	"
" 3rd "	6	"
" 4th "	8	"
" 5th "	10½	"
" 6th to 10th years, inclusive	12½	"
" 11th " 15th " "	15	"
" 16th " 20th " "	17½	"
" 21st " 25th " "	20	"
" 26th " 30th " "	22½	"
" 31st " 35th " "	25	"
" 36th " 40th " "	27½	"
" 41st " 45th " "	30	"
" 46th " 50th " "	32½	"

The foregoing are maximum rates applicable only in cases where all the water utilized comes from the Forest Reserve and the entire head developed results from the topography of the forest: In all other cases, deductions are made as follows:

> ' From the gross operation charge for any year calculated as above:
>
> (*a*) A sum bearing approximately the same ratio to one-half of such gross operation charge as the area of unreserved land on the watershed bears to the total area of the watershed as of the beginning of each year.
>
> (*b*) A sum bearing approximately the same ratio to one-half of such gross operation charge as the length of conduit outside the Forest Reserve bears to the total length of such conduit as of the beginning of each year.
>
> (*c*) A sum bearing approximately the same ratio to the balance remaining after said deductions " a " and " b " as the quantity of electric energy generated from water stored artificially by the permittee over and above what is generated by the natural flow, bears to all electric energy generated.
>
> The sum remaining after all the aforesaid deductions have been made constitutes the net operation charge for such year.

The rationale of the deduction for water stored artificially by the permittee is obvious. That for the first two deductions described is stated in an informal explanatory document of the Forest Service, as follows:

> Since the two advantages furnished by the Government are the maintenance of a steady flow from the forested watershed, and the fall resulting from the topography of the forest, one-half of the conservation charge is calculated as based upon each of these advantages. Therefore: (*a*) if a part of the watershed which supplies the power plant is outside of the national forest, the one-half of the conservation charge calculated upon the advantage resulting from the maintenance of the steady flow by the conservation of the forest cover is reduced proportionately and (*b*) if a part of the fall which the permittee is to use in developing power is outside of the national forest, the one-half of the charge which is based upon the fall is reduced proportionately.

THE IMPOSED RATES AS A TAX ON POWER ENTERPRISES

The proposed conservation charge, at least during the early years of the contract, cannot be regarded reasonably as constituting any very serious financial burden imposed upon the individual or corporation developing the water power. If power be sold at an average price of one cent per kilowatt hour, the maximum conservation charge during the first five years of operation is equivalent to a tax of 0.61 per cent of gross receipts. During the next five-year period, it is increased to 1.25 per cent of gross receipts and it increases gradually from this figure to a maximum of 3.25 per cent of gross receipts, which rate applies during the last five years of the 50-year life of the contract. The average charge during the fifty-year period is 2.086 per cent of gross receipts, if power be sold at the price assumed, *viz.*, one cent per kilowatt-hour.

If power be sold at an average price of 0.5 cent per kilowatt-hour the average conservation charge during the period of the lease becomes 4.172 per cent of gross receipts, and the maximum, which applies during the last five years of the lease, is 6.5 per cent of gross receipts.

It is a fair question, however, whether a more rational method, and one which in certain important respects would tend to produce better results, might not be devised. The plan in force obviously is open to several objections. Among these are:

(1) The imposition of a tax upon output means that the man who installs a highly efficient plant is called upon to pay a higher conservation charge than the man who wastes water by the installation of a cheap and inefficient plant. The effect of the conservation charge in influencing type of construction, and consequent effective utilization of the water, will probably be small but unquestionably that influence is exerted in the wrong direction;

(2) The proposed method of charging imposes a heavier burden upon the man who sells his power at a low price than upon him who sells it at a high price. The tax measured in percentage of gross receipts, is obviously twice as high in the case of the man who sells power at an average price of 0.5 cent per kilowatt-hour as it is in the case of a man who sells power at an average price of one cent per kilowatt-hour.

Both of these objections were pointed out in a paper read by Mr. F. G. Baum, before the American Institute of Electrical Engineers, at Atlantic City, N. J., in 1908, but the writer has not heard them referred to since, and they deserve careful consideration.

(3) Mr. Baum also calls attention to the fact that under the plan proposed by the Forest Service " the man who takes his power to a market, say one hundred to three hundred miles away must pay to the Government for the losses incurred in doing so and pays more than the man who sells to the home market. The man who reaches out with his power is equalizing conditions, just as railroads equalize conditions by their transportation facilities ".

The Italian law, recognizing this point, reduces the rental in the case of transmitted power. The basis of this reduction, as stated by M. Rene Tavernier, Chief Engineer, Department of Public Works, Republic of France, in his valuable article on "The Public Utility of Water Powers and their Government Regulation" (Water Supply Paper No. 238) is as follows:

> For power transmitted by means of electricity to distances greater than 10 kilometers (about 8 miles) there is granted upon the annual rental of 3 francs per horse power, a reduction calculated by multiplying the square of the distance expressed in kilometers by a fixed coefficient of 0.001. In no case shall the rental be reduced to less than one-half of 1 franc per horse power.
>
> Under this formula the minimum reduction, that is to 0.50 franc, will be attained in transmission over 50 kilometers (about 31 miles).

While the method of applying the "conservation charge" has been criticised in many quarters and while the objections above pointed out are valid, the method in force possesses undoubted advantage in the fact that it is definite and readily determined by reference to records which the permittee can easily keep. The charges moreover are adjusted to encourage development of the water powers by recognizing the fact that few, if any, can earn interest on the necessary investment from the start. In enterprises of this kind, the cost per unit of output generally decreases as the output increases. The forest service charge, recognizing this fact, is made small at the start and increases gradually. Except by reducing the average charge for the period, it would be difficult to devise a plan less onerous for the permittee.

(4) While the imposed charge could not be regarded as excessive, if the power developed were entirely, or even very largely, dependent upon the preservation of forest cover upon the watershed, it represents a high rate when measured in comparison with the increase in commercial value of the power, which, under ordinary conditions, is due to the forest. If, for illustration, it be assumed that under average conditions "forest control" adds 25 per cent to the value of the water power, a tax averaging 4.172 per cent of gross receipts is a tax of 20.86 per cent of the gross value contributed by the forest.

(5) The tax is imposed upon power from all "forest reserve lands," regardless of the actual condition of the forest upon which it is based. Obviously, therefore, a uniform tax must be very much heavier in some cases than in others, as compared with the benefit upon which it theoretically rests.

(6) It tends to retard utilization of water powers and stimu-

lates the use of coal for power purposes—a result which is in direct contravention of the primary object of conservation.

(7) Something less than one-half the public domain is included within the limits of the forest reserves. To secure maximum revenue and to minimize the average retarding effect upon utilization of these water powers resulting from a system of rental, any charges which may be imposed by the Federal Government upon water power appropriation should apply to all public lands.

The author has expressed the opinion that the imposed charge would not be regarded as excessive if the power developed were entirely, or even very largely dependent upon the preservation of forest cover upon the watershed. In his judgment, however, that effect has been very greatly exaggerated by the majority of writers who have endeavored to instruct the public regarding the subject.

To sustain the announced theory of the Forest Service, it is evident that the value of the water power should be directly dependent upon forest control of the run-off. Obviously the statement that " the forest cover on the steep slopes acts like a giant sponge, absorbing the excess of rainfall in the wet season and giving it out to the thirsty lands in the dry season " and that the " power company which puts its plant on national forest land gets from the Government the guarantee of a steady flow of water " are highly figurative.

The extent to which forest cover and other surface conditions which tend to regulate run-off, succeed in equalizing stream flow, is illustrated in the following tabulated statement, showing in the case of ten (10) fairly representative rivers of the Atlantic and Pacific slopes the maximum, average and minimum run-off in second feet per square mile for periods of five consecutive years and the minimum run-off expressed (*a*) in percentage of maximum run-off and (*b*) in percentage of average run-off.

Without attempting to discuss the complex conditions which determine the relations of maximum, average and minimum run-off, it is evident that in no case does existing forest cover or any other surface condition effectively equalize the flow.

As regards the relation of minimum to maximum run-off, the most favorable case, that of the Merrimac river, shows a minimum flow of 1.86 per cent of the maximum, while for the ten rivers the minimum flow averaged is 0.837 of the maximum flow averaged. As regards the relation of minimum to average run-off, the most favorable case, the Yadkin, shows 17.6 per cent while the average of the ten (10) rivers is 9.95 per cent.

The effect of forest cover in adding to the commercial value of a water power, results from two facts, namely, first, the fact that an increase in minimum run-off reduces the necessary investment in auxiliary steam or other power plant; second, the fact that some portion of the flood waters, which otherwise would flow past the power plant, at a time when the water available exceeds the amount needed, is held back long enough to permit its commercial utilization. As regards the first of the two conditions referred to, if we assume that auxiliary steam power is

FIVE YEAR RUN-OFF TABLE

River	Gauging station	Drainage area sq. miles	Maximum run-off sec. ft. per sq. mile	Average run-off sec. ft. per sq. mile	Minimum run-off sec. ft. per sq. mile	Minimum in per cent of	
						Max.	Ave.
Kennebec......	Waterville, Me.	4380	17.5	1.96	0.0388	0.222	1.98
Merrimac.... .	Franklin Junction, N. H.	1460	16.93	1.998	0.315	1.86	15.77
Connecticut....	Holyoke, Mass.	8144	14.12	1.623	0.258	1.83	15.9
Susquehanna...	Binghamton, N. Y.	2400	19.62	2.044	0.0187	0.095	0.916
Yadkin........	Wilkesboro, N. C.	500	36.8	2.446	0.43	1.17	17.6
Savannah......	Augusta, Ga.	7294	18.83	1.56	0.198	1.05	12.7
Black Warrior.	Near Cordova Ala.	1900	26.0	1.515	0.01473	0.0567	9.73
Feather.......	Oroville, Cal.	3640	29.0	2.354	0.33	1.14	14.0
Yakima.......	Near Yakima, Wash.	3300	19.37	1.322	0.1926	0.995	14.56
Naches........	Near North Yakima, Wash.	1120	19.55	1.489	0.0268	0.137	1.8
			21.772	1.8311	0.18226	0.837	9.95

used to insure a continuous supply equal to the average which a given head on each of these rivers can develop, it will be seen that such auxiliary plants must be capable of producing power in an amount ranging from 82 per cent to 98 per cent of the water power. The difference, therefore, between the best and the worst case among these typical streams affects the cost of the auxiliary plant to the extent of 16 per cent of the cost of a steam plant capable of developing the same output as the water power.

As regards the effect of forest cover upon the relative proportions of energy output from the water power and from the auxiliary steam plant, the conditions are so complex as to prevent profitable generalization. The holding back of a portion of the flood waters saves fuel and other operating costs of the auxiliary steam plant or reduces the artificial storage required. While it is evident that this effect, under the best conditions existing upon any of the watersheds, drained by the streams referred to in the table, is not such as to justify the theory that the forest cover is the principal factor affecting the value of the water power, the author would not be justified, from present knowledge, in attempting to fix its average effect upon that value.

FEATURES OF THE PRESENT REGULATIONS WHICH SHOULD BE CHANGED

Permit Non-Transferable (*Clause* 15).

Clause 15 of the power agreement now in force reads as follows: "The permit here applied for shall be non-transferable (U. S Revised Statutes, Section 3737) and shall be subject to all prior valid claims which are not by law subject thereto".

The aim in view of course is to prevent monopoly, as a result of which an artificial price might be maintained higher than the average which would be fixed by competition of similar developments in the same market.

If effective, it is obvious that this requirement must retard development. The economic reasons which demand that water powers on the same stream should deliver their output to the same network of distributing circuits in many cases are material, and those which demand that the output of developments on different streams should be similarly combined are even more weighty. In the former case, under certain conditions, as has been pointed out by Mr. W. S. Lee, in his paper before the American Institute of Electrical Engineers, (PROCEEDINGS for

April, 1910), the net output of a stream effective for commercial purposes may be considerably increased. In the latter case, owing to the fact that the relative run-off of neighboring watersheds sometimes varies widely during successive years, the reliability of the supply of power to the user is materially increased by combination. To put the matter another way, if combination be not permitted the aggregate investment in auxiliary steam plants or gas engine plants must be largely increased, which obviously is bad economy and means an increase in cost of power not only to the producer but also to the user.

By electrically combining the output of a considerable number of water powers, interruptions of service, due to accidents to flumes, or to transmission circuits, are decreased.

The clause, in my judgment, should be modified by permitting transfer, subject to approval by the government. The right of a state or municipality to fix charges, in the case of a public utility company selling its product within the limits of such state or municipality, has been established by decisions of the Supreme Court of the United States. The danger that American communities in general, knowing this fact, will submit for any great length of time to the imposition of rates that are really extortionate, is not comparable to the economic loss which is certain to result from the imposition of conditions limiting the opportunity for profitable investment of capital. In this connection it is evident that even an assumed water power monopoly of the largest conceivable size must sell its power at a cost lower than the cost of competing power produced by steam plants.

The established right of a state or municipality to fix rates at which power is sold is an absolute protection applicable by local governments best able to judge the conditions which determine what is an equitable charge.

CONTINUOUS OPERATION OF PLANT.

Clause 18 reads as follows:

> The permittee shall, except when prevented by the act of God or the public enemy, or by unavoidable accidents or contingencies, continuously operate for the generation of electric energy, the works to be constructed under the permit hereby applied for, in such manner as to generate after such generation begins, not less than the following percentages of the full hydraulic capacity of the said works measured in kilowatt hours; in the first year . . . per cent; in the second year . . . per cent; in the third year . . . per cent; in the fourth year . . . per cent; in the fifth year . . . per cent; and in every year thereafter . . . . per cent.

The object in view is to prevent a power company increasing its prices by creating an artificial power famine and to secure full utilization of the available power. Some permits have specified that not less than twenty-five per cent of the full hydraulic capacity, measured in kilowatt hours, must be generated; others as much as seventy-five per cent, depending upon special circumstances supposed to govern the case.

In many cases this clause presents serious difficulty to the power company. In the majority of instances with which the writer has been personally familiar, it has been extremely difficult, if not impossible, to predict either maximum or minimum limits of the growth of power output. Circumstances may be conceived under which a power company, operating not only the plant covered by the permit but also other plants, might shut down the first named to produce temporarily an artificial scarcity of power, but the fact that this would mean an idle investment would make this a rare case. If it be necessary to retain such a clause, it should be accompanied by a provision permitting, with the consent of the government, a reduction in the percentages originally fixed.

While discretionary power to make conditions upon which capital has been invested more onerous will retard or prevent development, the bestowal upon a Secretary of Agriculture or a Secretary of the Interior, of power to make those conditions less onerous involves no corresponding public risk, since that Secretary would destroy himself politically who should grant such authorization without proper cause. No power company can afford to invest capital under a contract which leaves it in the power of a government official to increase the burdens of the enterprise within the term covered by the permit, but the government and the public can well afford to bestow upon a responsible official authority to reduce those burdens upon proper application and presentation of valid reasons.

TERM OF PERMIT

Clause 20 of the permit in force reads as follows:

> " The permit hereby applied for shall cease and be void, upon the expiration of fifty years from the date of approval hereof, but it may then be renewed in the discretion of the duly authorized officer or agent of the United States, and upon such conditions as he may in his discretion fix: *Provided* that such officer or agent, in fixing such conditions shall consider the actual value at that time for power and all other purposes of the lines and rights of way within National Forests occupied and used under the permit hereby applied for and the actual value at that time of all

improvements lawfully made by the permittee within National Forests under the permit hereby applied for, but neither the property of the permittee, if any, outside of National Forests, nor the permit, franchises, bonds, capital stock or other securities of the permittee shall be considered in fixing such conditions."

It will be noted that this clause contains no provision for taking care of the contracts which may be in force between the permittee (or his successor) and his customers at the expiration of the fifty-year period, nor does the author find any provision covering this point elsewhere in the power agreement. It is obvious that by its absence the value of the permit during the latter years of its life, is materially impaired. Power contracts are frequently, in fact generally, executed for periods of not less than five years and frequently for ten or even twenty years.

The contract agreement should include a clause guaranteeing for a period not less than five years subsequent to its termination, the fulfillment of contracts between the permittee and customers existing at that time.

THE PERMIT REVOCABLE

Under the law as it now stands the Forest Service can grant to an individual or corporation seeking to develop water power from Forest Reserves only a permit revocable by the Secretary of Agriculture in his discretion. The so-called "Second right-of-way" act is entitled "An Act relating to rights-of-way through certain park reserves and other public lands," and bestows authority in this matter upon the Secretary of the Interior. A later law, approved February 15, 1901, transferred to the Secretary of Agriculture responsibility for the execution of all laws relative to national forests.

No argument is necessary to demonstrate that a permit revocable in the discretion of the head of a department is not an adequate basis for financing an enterprise requiring investment of capital. This vital defect of the existing law to-day stands squarely in the path of legitimate and praiseworthy enterprise seeking to develop and utilize our many water powers from forest reserves now wasted. Every proper influence should be brought to bear by those interested in the true conservation of our natural resources to secure a modification of the law removing this otherwise insuperable barrier.

AN ALTERNATIVE PLAN

The man who criticises adversely a plan which has been elaborated by others is not necessarily under obligation to suggest an alternative and, moreover in the judgment of the author, any plan which imposes a tax upon water power or fuel is at best of doubtful wisdom. Assuming, however, that upon careful consideration the American people should decide definitely and finally to impose a tax upon natural resources of the public domain, to be used in conserving and developing those resources, it is perhaps not improper to suggest the outlines of a plan which from the standpoint of public policy appears preferable to that now in force. The essential features of the plan which he would suggest are the following:

(1) A tax imposed on all sources of power found upon public lands—a royalty on coal mined and a rental upon water power. The charge for water power to be based not upon an indefinite and disputed relation of forest covering and commercial value of the power, but upon the fact that the Government needs revenue to develop and conserve our natural resources, owns the power, and, as owner, possesses an unquestionable right to impose a charge for its use. The Federal Government is now selling coal lands on the public domain at prices which, on the average, approximate one-tenth of one cent per ton of the coal which it is estimated the property can commercially yield. If the coal be used to produce power under average conditions this tax is substantially equivalent to 0.5 cent per 1000 kw-hr. as against an average rental of 20.86 cents per 1000 kw-hr now imposed in the case of water power. The theory of conservation unquestionably points to an increase in the price fixed for coal lands or a decrease in water power rental, or both. By adjusting the charges for coal and water power to approximate equality, as measured by their respective ability to produce power, the tendency of the present method to stimulate the use of coal for power purposes as against the use of water power—a tendency which, as the author has stated, is in direct contravention of the fundamental idea of conservation—will be avoided and the aggregate revenue ultimately available to the Federal Government for the purpose contemplated will be enormously increased.

The general features of the present contract agreement enforced by the Forest Service as regards fifty-year limit of the period of appropriation should be preserved. The other restrictions now imposed should also be retained except that certain clauses should be modified to meet the practical objections which have been pointed out, in so far as mature consideration may determine the validity of those objections.

The proceeds of royalties upon the sale of coal land and forest products and rentals of water powers should be used to conserve our national resources by development under broad and systematic plans—to conserve forests, build dams, improve navigation and irrigate the arid lands.

(2) The charge imposed upon water powers to be based upon the amount of water appropriated and the effective head resulting from the topography of the Government lands concerned.

Under the present plan, it is necessary to measure the water used in order to fix the third deduction from the charge based upon output. The difficulty of measuring water, therefore, must be met and it is as easy to fix the second-feet appropriated as to fix the deduction allowed for artificial storage by a permittee.

Under this plan it would be to the interest of the permittee to install a plant of high efficiency and not a plant of low efficiency as the present method of charging suggests.

An important practical point in this connection is the fact that the estimate of competent Government engineers, discussed with and agreed to by the permittee would constitute a safer basis for the investor who may undertake to finance the enterprise than he now has in the data submitted for his consideration by the promoter.

(3) There is a third suggestion which perhaps may be worthy of consideration in view of the fact that conditions as regards cost of development and characteristics of the market for power differ so widely in various parts of the country. That suggestion is that the Government engineers of the departments or bureaus concerned prepare comprehensive preliminary plans for the development of water powers of a given watershed and that these water powers collectively or severally be leased to the highest bidder, the Government, of course, reserving the right to reject all bids.

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HEADLIGHT TESTS

BY C. FRANCIS HARDING AND A. N. TOPPING

The Indiana Railroad Commission, having been instructed to investigate and rule upon the compulsory use of more powerful headlights on steam locomotives operating in the State of Indiana, requested that both road tests and laboratory tests be carried out by the Engineering Schools of Purdue University, under the direction of Dean C. H. Benjamin, to determine the effect of such powerful headlights upon the interpretation of signals and upon the ability of the engineer to see and recognize obstacles upon the track in front of the locomotive. These tests which were carried out in the fall of 1909, consisted of two distinct groups as follows:

Group 1. Road tests carried out on the St. Louis division of the Big Four Railroad for the purpose of comparing effects noted above of oil and electric headlights under actual operating conditions.

Group II. Laboratory and out-of-door tests carried on by the School of Electrical Engineering, Purdue University, under the direction of the authors to determine the photometric and spectrophotometric values of the above headlights as well as corresponding values for reflected light from signal roundels.

Since the completion of the above tests, the authors have carried out similar but more detailed tests on the above headlights together with a number of new types. In the belief of the authors of this paper that little has been made public along these lines, and that many engineers will be interested in this subject, the result of the latter tests are herein set forth prefaced by a brief abstract of the previous road tests.

GROUP I—ROAD TEST

The following road tests were carried out during the night of October 13th, 1909 on the main line of the Big Four Railroad near Indianapolis, Indiana. Independent observations of signal aspects were taken by eleven observers seated in an open front observation car provided with headlights of different types placed at the same distance above the track as when mounted upon the locomotive. These observations were later compared and averaged and the results of the same briefly summarized. For detailed information regarding these road tests reference should be made to the paper by Dean C. H. Benjamin, read before the Western Railway Club and published in the April PROCEEDINGS.

Procedure. Test numbers 1 *to* 6 *inclusive were carried out in the following manner:*

The observation car was run back 5,000 feet from the home signal and a long blast of the locomotive whistle sounded. The colors of the home signal were then changed by a committee appointed for this purpose which remained at the signal. The observers in the observation car did not know the changes that were to be made in the colors. After sufficient time had elapsed for the signal to have been changed, the car was moved toward the home signal and short stops were made at predetermined intervals. At each stop, each of the eleven observers recorded independently the aspect of the home signal as he saw it. These records were collected after each test and later compared with one another and with the actual aspect of the signal in each case.

Test No. 1. *Observation of Colors of Home Signal at Distances Ranging from* 300 *to* 5,000 *Feet with Electric Headlight on Observation Car and the Opposing Electric Headlight* 200 *Feet in Front of Home Signal.*

From a comparison of the observations made of a number of different aspects in this test, where both headlights were of the electric type, it was noted that at distances of 3000 ft. or over the signals were invisible; that correct interpretation of the signals occurred at distances ranging from 800 to 1500 ft. from the home signal, depending upon the observer, and that at a distance of 800 ft. identification was practically unanimous. The interesting feature about this test is the fact that at distances of from 400 to 800 ft. many observers noted green signals where there was none displayed; at 600 ft. eight of the eleven observers recorded a green signal where no light existed, although at this point a green roundel had been placed with no signal light behind it. This so-called green phantom is the effect often noted by engineers operating locomotives with powerful headlights and is supposed to be due to the reflection of the light transmitted from the headlight to the unlighted green roundel and thence back to the eye of the observer or locomotive engineer. No such effect as this was noted in tests Nos. 2, 4 and 6 where the observation car was provided with an oil headlight.

Test No. 2. *Observation of Colors of Home Signal at Distances Ranging from* 300 *to* 5,000 *Feet with Oil Headlight on Observation Car and on Opposing Electric Headlight* 200 *Feet in Front of Home Signal.*

Under the conditions of this test the results were quite similar to those of test No. 1, with the exception that no phantom signals were noticed. One observer only interpreted the signal correctly at a distance of 3000 ft., and at 600 ft., practically all observations were correct.

The results of this test show that distances at which signals can be correctly interpreted are affected more by the character of the opposing headlight than by that of the headlight on the observation car, and further, that phantom signals are due to the reflected light from the unlighted roundels made noticeable by the great intensity of the electric headlight.

Test No. 3. *Observation of Colors of Home Signal at Distances Ranging from* 300 *to* 5,000 *Feet with Electric Headlight on Observation Car and the Opposing Oil Headlight* 200 *Feet in Front of the Home Signal.*

The correct aspect of the home signal was generally recognized in this test at the full distance of 5,000 ft. and identification was practically complete at 3000 ft. Here again it should be noted that a considerable number of phantom signals were recorded due to reflection, these appearing at distances ranging from 600 to 800 ft. The above results indicate that in case the locomotive engineer is called upon to read signals at the time he is meeting a train equipped with an electric headlight, the distance and therefore the time in which he must make his correct observation is much less than when the opposing headlight is of a less powerful type.

Test No. 4. Observation of Colors of Home Signal at Distances Ranging from 300 *to* 5,000 *feet with Oil Headlight on Observation Car and the Opposing Oil Headlight* 200 *Feet in Front of the Home Signal.*

Under the conditions of this test practically all the observers were able to read the signals correctly at the full distance of 5,000 ft. and identification was unanimous at 2,000 ft.

Test No. 5. Observation of Colors of Home Signals at Distances Ranging from 300 *to* 5000 *Feet with Electric Headlight on Observation Car and no Opposing Headlight.*

Practically complete identification of the home signals was made by all observers at the full distance of 5,000 ft. In spite of the fact that there was no light behind one of the green roundels during the test, several observers recorded a green signal at distances ranging from 400 to 800 ft.

Test No. 6. Observation of Colors of Home Signals at Distances Ranging from 300 *to* 5000 *Feet with Oil Headlight on Observation Car and no Opposing Headlight.*

This test represents the best condition for the reading of signals since they were all read correctly by all observers at 4,000 feet and no phantom signals due to reflection were observed.

Classification Signal Tests

Tests Nos. 7 to 10 inclusive were made to determine the distance at which the classification signals on the front of the approaching locomotive could be read with the two types of headlights. As the classification signals displayed on the front of the locomotive indicate either that a train is a special or that another train is following on the same schedule, it will be noted that the correct reading of these signals is of extreme importance. The procedure in all of these tests was as follows:

The observation car was run back several thousand feet and a long blast of the whistle sounded. An engine with an opposing electric headlight displaying classification signals located at the side of the smoke box was run on to the same track. Upon notice from the committee which prepared the classification signals, the observation car was moved forward slowly and first stopped at a distance of 400 ft. from the opposing locomotive. Additional stops were made at distances of 100 ft. until observations became unanimous in reading the classification signals.

Test No. 7. Classification Signal Test with Electric Headlight On Observation Car and Opposing Electric Headlight on Locomotive.

In this test both white and green classification signals were displayed. At 400 ft. only four observers saw the white light and at 300 ft. only eight could see it. None of the observers saw the green light at a distance of 200 ft., while nine of the eleven observers saw the white light at this distance. The above test indicates that the opposing electric headlight limits the distance in which the engineer can correctly observe the classification signals to a very small margin. The difficulty in observing the green signal was possibly due to the predominance of green rays in the headlight used. The spectrophotometric analysis of this light is shown in Table IX.

Test No. 8. Classification Signal Test with Electric Headlight on Observation Car and Opposing Oil Headlight on Locomotive.

The green and white classification signals displayed in this test were read correctly without difficulty by all observers at 400 ft., most of the observers having seen the signals at 800 ft. The ability to read classification signals correctly, therefore, is much greater with the oil headlight opposing than in the case of the more powerful electric headlight.

Test No. 9. Classification Signal Test with Oil Headlight on Observation Car and Opposing Oil Headlight on Locomotive.

The green and white classification signals were correctly identified by all observers at 600 ft. while some observers noted signals correctly at distances ranging from 1,200 to 2,200 ft. It is interesting to note from this test that with nothing more powerful opposing than an oil headlight, with an oil headlight on the observation car, the distance at which classification signals could be read was increased over that with an electric headlight on the observation car by about 50 per cent.

Test No. 10. Classification Signal Test with Oil Headlight on Observation Car and Opposing Electric Headlight on Locomotive.

Two white classification signals were displayed and were seen correctly by all observers at 300 ft., while some observers saw them correctly at distances ranging from 600 to 800 ft. It should be noted from this test that the inability to distinguish correctly the green signal in Test No. 7 is not due to its position upon the locomotive, but rather to its color, since the two white signals in this test were distinguished at the same distance.

OBSTRUCTION TESTS

It has been argued that more powerful headlights for locomotives, by increasing the distances at which obstructions may be seen on the track, may prevent the occurrence of accidents. The following tests were made to determine the exact distance at which various objects on the track in advance of the locomotive could be seen and identified. It should be noted that in these tests the observers were on the lookout for some obstruction and observations were made at times when the car was at a standstill, both of which conditions were obviously more favorable to the correct detection of objects on the track than in ordinary railroad practice. The procedure in all of these obstruction tests was as follows:

The observation car was run back a distance of 2,000 ft. and the usual signal given with the whistle. Different objects were then placed upon the track in the various tests, the approximate localities of the obstructions being known to the observers, who, however, had no knowledge of the kind of obstructions which were to be used. When signalled by the committee which had the preparation of the obstacles in charge, the observation car was moved slowly forward and stopped at regular intervals. Independent records were made at each stop of whatever obstruction was noted by the observer. Note was also made of the distance at which the obstruction could be identified. An electric headlight was used on the observation car throughout these tests.

Test No. 11.

A speeder was placed on the track for this test. Comparison of the records shows that this was first noticed by about one-half of the observers at a distance of 700 ft. and by the remainder at 500 ft. It was not fully identified, however, until the car was within 300 ft. of the obstruction.

Test No. 12.

A car was backed on a siding so as not to be entirely clear of the main track. The majority of the observers did not notice this obstruction until the observation car was within about 900 ft. of it. Those who were not railroad men, or at least familiar with railroad practice, did not recognize this car as an obstruction, so that the test was not conclusive.

Test No. 13.

Two sacks stuffed with straw about the size of a man's body were placed between the rails and remained unidentified by all but two observers until the car was within 250 ft. of the obstruction.

Test No. 14.

Two coal cars were backed on the main track for the final test. This obstruction was noticed by practically all observers at a distance of 1,300 ft. but was not fully identified until the observation car was within 900 ft. of the obstruction.

CONCLUSIONS

The following general conclusions seem warranted from the results of the above road tests:

1. That a powerful headlight on a locomotive has one marked disadvantage, namely, that it causes reflections from glass roundels and lenses, thereby producing false or phantom signals. It seems likely that these are partly due to the intensity and partly to the spectral composition of the light.

2. That a powerful opposing headlight adjacent to block signals so obscures the latter as to make it difficult to read them correctly at distances exceeding 1,000 ft.

3. That an opposing oil headlight of ordinary intensity allows such signals to be read correctly at 4,000 ft. or less.

4. That even with no opposing headlight, the distance in which the signal can be read correctly is slightly reduced by the use of a powerful headlight.

5. That a more powerful headlight on an approaching engine obscures the classification signals on that engine to a marked degree. This is particularly true of green signals in the glare of a powerful headlight whose spectral intensity is high in green.

6. That an opposing oil headlight of ordinary intensity allows either white or green signals to be read at a distance of 400 ft. or even more.

7. That obstructions on the track cannot ordinarily be seen with a powerful electric headlight at a sufficient distance to

prevent accidents, since a train travelling at a high rate of speed cannot be stopped in the distance at which obstacles sufficiently large to cause a wreck were first detected.

Group II—Laboratory Tests

This group of laboratory tests consists of four separate series made on seven different lamps of various types. The lamps are referred to in this paper by number and may be briefly described as follows:

No. 1. Luminous arc, upper electrode copper, lower electrode presumably magnetite composition.

No. 2. Carbon arc, carbons inclined 45 deg. to the horizontal.

No. 3. Luminous arc, similar to No. 1.

No. 4. Electric arc, upper electrode carbon, lower electrode copper.

No. 5. Kerosene oil lamp.

No. 6. Acetylene lamp.

No. 7. Luminous arc, same as No. 1, but instead of being fitted with a reflector, supplied with a lens.

Each of the above headlights was fitted with a reflector supposedly parabolic in shape, except No. 7 which, as before noted, was arranged with a lens before the lamp. The reflectors on Nos. 4, 5 and 6 were polished silver, and those on Nos. 1, 2 and 3 seemed to be polished aluminum.

Four series of tests were made upon these lamps as follows:

Test No. 15. A determination of the illumination produced by the headlight at a fixed point in the axis of the reflector.

Test No. 16. A determination of the total light flux generated by the lamp.

Test No. 17. A determination of the illumination produced along a course of 1300 ft. in front of the headlight.

Test No. 18. A spectro-photometric analysis of the light from each lamp.

In addition to the above, tests were made upon signal roundels taken from service.

Test No. 19. A spectrophotometric analysis of the light reflected from roundels.

Test No. 20. A determination of the reflection coefficients of roundels with and without signal lamps.

It is not necessary to point out in this paper the greater difficulties in obtaining exact results in photometric and especially in spectrophotometric analyses of the light furnished by the electric arc lamp over those encountered in the comparison of most other illuminants. This is particularly true in the case of the electric arc headlights where not only the fluctuations of the arc itself are the direct cause of sudden variations in intensity, but also because of the fact that the arc may at times get out of the focus of the reflector and thus greatly multiply the variation in intensity of the reflected light. It should be pointed out, therefore, that the accuracy is probably greater in the following tests made with oil and acetylene headlights than in the case of the electric arc headlights, although every precaution was taken in all tests to obtain constant reading conditions. The results recorded in the following pages represent the average of a number of readings taken by several observers.

Test No. 15. *A Determination of the Illumination Produced by the Headlight at a Fixed Point in the Axis of the Reflector.*

In this series of tests the headlights were mounted in a dark room arranged for photometric purposes in such a manner that the axis of the reflector passed through the position of a Lummer-Brodhun type of sight box located at the opposite end of the room at the fixed distance of 25.7 feet from the position of the lamp. To balance the illumination of the arc, on the opposite side of the photometer screen, an incandescent lamp of appropriate intensity maintained at a definite voltage was arranged to be controlled by the observer at the sight box. Also, under the control of the observer and moving with the lamp was an electromagnetically operated punch enabling him to record on a sheet of paper upon a drum the position of the lamp corresponding to a photometric balance between the headlight and the comparison lamp. This device was described by Matthews in a paper before the A.I.E.E. in 1901.* By its means a large number of independent observations corresponding to each condition were easily taken and thus a proper average obtained. With the hope of reducing the large number of possible errors in photometering and electric arc, the substitution method was used throughout, *i.e.*, the comparison lamp while on the bar in working position was frequently compared with a standardized lamp put in position on the headlight side of the sight box.

On account of the extremely high illumination produced by the headlight, it was found necessary to reduce the intensity at the sight box in most cases by the use of the well known rotating sectored screen. The only exception to this was with the oil headlight. The constant of the rotating screen was carefully determined and the value checked.

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*"An Improved Apparatus for Arc Light Photometry," Chas. P. Mathews, TRANSACTIONS, A.I.E.E., Vol. XVIII, p. 677.

The headlights were all operated as nearly as possible under conditions as specified by the manufacturers. Thus, lamps Nos. 1, 2, 3 and 7 were operated in series with their respective resistances on a pressure of 550 volts, lamp No. 4 with a constant current of 28 amperes, No. 6 with a gas pressure from a tank supplied by the manufacturers, and No. 5 with as high a flame height as could be maintained without the lamp smoking.

From the theory of the reflector, it was decided that the light probably did not follow the law of inverse squares, and since the law of the illumination was to us unknown, it was decided not to attempt to express the intensity of the headlight, but rather the intensity of the illumination produced by it. It was hoped that time would permit the inclusion in this paper of the results of tests planned and in progress for the determination of the law or laws of the variation of the light from these reflectors, but it was found impossible to get these tests finished in time.

The results of test No. 15 are found in Table I expressed in candle-feet of illumination. Considerable fluctuation of the intensity was noted during the test on each lamp and the average value given in the table is the average of from twenty to eighty readings. It was thought that the range of variation for any one lamp might be of interest and the maximum and minimum values of the illumination are accordingly given in the table together with the percentage variation above and below the average.

In column 19 of the same table is found the ratio of the illumination of each lamp to that of the oil lamp, which on account of longer and more common use was taken as a standard for the others. It is of interest to note that the highest illumination was produced by No. 7, and that the illumination from this lamp is a little more than twice as great as the illumination from No. 1, the only difference between the two lamps being that No. 7 is equipped with a lens and No. 1 with a reflector. It is also to be noted that the ratios of the illumination produced by the arc headlights to that of the oil light are of the same order, varying from 23.5 to 49. It is not to be supposed, however, that these ratios would be the same at all distances in front of the headlights, in fact, the results of test No. 17 show quite the contrary. This likely is due to the fact that the law of variation of the intensity of the light is, or may be different for each reflector.

Test No. 16. *A Determination of the Total Flux Generated by the Lamp.*

To make this test, the reflector and all unnecessary equipment was removed from the headlight which was then hung in a circle of mirrors constituting a portion of the mirror photometer described by Matthews in the paper previously cited. These mirrors were located 15 deg. apart enabling the intensity of the light from the lamp to be determined at angular steps of 15 deg. above and below the horizontal. The coefficients of reflection of the mirrors had been previously determined.

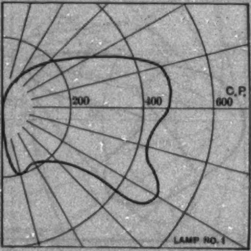

Fig. 1—Distribution of lamp No. 1

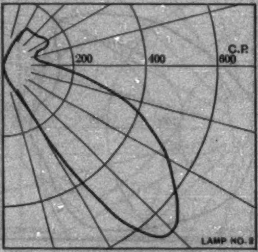

Fig. 2—Distribution of lamp No. 2

The sight box of the photometer was located at the same point as in test No. 15, and the settings were taken in the same manner, with the lamp operating normally, and with all the mirrors covered except those corresponding to the particular angle in which the intensity was being determined. The light from the uncovered mirrors was reflected directly to the photometric screen in the sight box. The intensity determined is from an average of from 20 to 50 independent settings of the photometer taken during a time varying from 5 to 10 minutes. It is believed, therefore, that the results thus obtained represent the average condition of operation.

From these intensities a distribution curve of light from each lamp was plotted and the Kennelly method for determining the total light flux in spherical candles was applied. This method is described by its originator in the Transactions of the Illuminating Engineering Society. In using this method the distribution curve was divided into 15 deg. zones which, it was thought, would insure the accuracy of the determination to a point equal to that ordinarily obtained in photometric work. This method of determining the total light flux from the distribution curve was preferred to the method of obtaining it by a single setting on account of the fact that, in some of the lamps, a shadow was cast at the extreme angles above and below the horizontal by a part of the frame work supporting the arc mechanism. In the method used, the error which would have been introduced by using the single setting method was reduced by assuming such values of intensity at these angles as seemed likely from the trend of the distribution curve. It is not claimed that this can give results of extreme accuracy. It is true, however, that a small variation in the intensities in these directions has little effect upon the total light flux as determined.

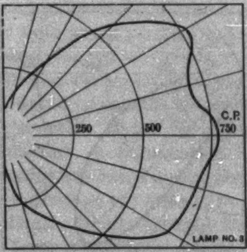

Fig. 3—Distribution of lamp No. 3

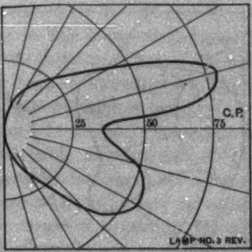

Fig. 4—Distribution of lamp No. 3 (reversed)

The distribution curve for No. 2 could not be obtained with the arc in its normal position because of the fact that this position is with the carbons at an angle of 45 degrees from the vertical. On that account, a distribution curve taken in the vertical plane cannot be used to determine the mean spherical candle power. To obtain a distribution curve for this lamp, it was mounted so that its carbons hung in a vertical plane and the distribution curve taken as in the other types of lamp. It was not considered, however, that this curve would coincide with the curve that would obtain were the lamp hanging in its normal position, because of the fact that the regulating mechanism has its center of gravity disturbed by this change resulting in a length of arc different from that in normal operation. The value of the mean spherical candle power obtained from this curve is found in Table 1 Column 14. An attempt to correct for this abnormal condition was made by taking the intensity of the lamp when suspended normally in a direction corresponding to an angle of 37½ deg. from the horizontal with the carbons in a vertical position. The value thus obtained was considerably larger, than the intensity at the same angle with the lamp in its abnormal position as in the first case, the ratio between the two being 1.35. The intensities taken in the first determination were then multiplied by this ratio and the mean spherical candle power determined from these corrected values. Naturally, this is a considerably higher value than that obtained at first. It seems likely that the value thus obtained is more nearly correct. The values of these light fluxes are found in Table I column 14, and in column 15 are found values of the illumination at the photometer sight box corresponding to the total flux found in column 14. These values of illumination were obtained by dividing the light flux for a given lamp by the square of its distance from the photometric screen. Thus for lamp No. 1, 790 mean spherical c.p. $\div (25.7)^2 = 1.197$. This may be called the hypothetical value of the illumination were the reflector absent. To obtain an idea of the effectiveness of the reflector the actual values of illumination obtained at the fixed point with reflector on the lamp were divided by the hypothetical values in column 15, giving results shown in column 22. The value thus obtained may be called the "Multiplying Factor of the Reflector". It

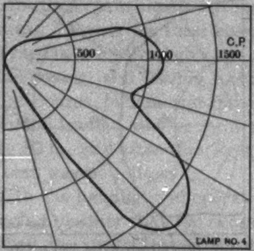

FIG. 5—Distribution of lamp No 4

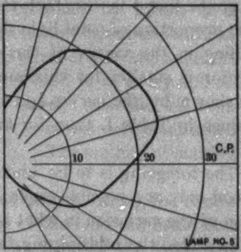

FIG. 6—Distribution of lamp No. 5

will be observed that this factor is not the same for all reflectors, varying from 58.7 for No. 4 to 241 for No. 2.

From the exceedingly high value of this factor for No. 2 the comparatively low total flux of this lamp and the peculiar distribution of light from a carbon arc, it seems probable that the value of this factor is a function of the distribution of the light about the source. In this particular case the inclination of the carbons from the vertical, causes the most intense ray to fall directly in the vertex of the reflector. In no other case does this occur. In the case of No. 4 which has a distribution curve very similar to No. 2, since the electrodes are vertical, the strongest ray, *i.e.*, 45 deg. below the horizontal, does not strike the vertex of the reflector. It may be noted in this connection that the multiplying factor of this reflector is the lowest of any. An explanation of this condition may be found in the fact that the proportion of total light flux falling in the vertex of the reflector is smaller for this lamp, as shown by the curves and the values in Table I, than for any other.

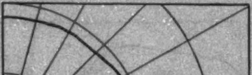

Fig. 7—Distribution of lamp No. 6

The foregoing is to be understood only as a possible explanation of the variation in what has been called the multiplying factor of reflectors which were clean and in apparently good working condition.

Test No. 17. *A Determination of the Illumination Produced along a Course of* 1300 *Feet in Front of the Headlight.*

The nature of this test, which was conducted on moonless nights, is much the same as test No. 15, differing from it principally in the method employed. The attempt was made to duplicate as nearly as possible conditions as to position of headlight and illumination produced thereby as they would occur in practice.

In pursuance of this idea, a tower platform 15 ft. 6 in. high was built out of doors at one end of a course 1,300 ft. in length. The reason for selecting this height was that on the locomotive used in the road tests the headlight was mounted 11 ft. 6 in. above the track. The sight box of the portable photometer was four ft.

high and by placing the headlight on the platform at a height of 15 ft. 6 in., it was possible to determine the illumination as it would occur on the track. The headlights designed for electric traction use were mounted at a height above the photometer level corresponding to that at which they are normally carried on the car.

The photometer used was a Lummer-Brodhun mounted on a tripod. For the purpose of excluding stray light it was fitted with a hood consisting of two tubes of sheet iron 20 in. long by two inches in diameter, blackened within with lamp black. These tubes were attached to the sight box, one on each side entirely covering the opening so that no light could fall upon either side of the screen which did not pass through the tubes.

For comparison, standardized incandescent lamps were used, which during the tests were maintained at a voltage corresponding to their previously determined intensity by means of a rheostat. Power for these comparison lamps was obtained from a storage battery through a line erected parallel with and adjacent to the course, and having sockets connected in at every 100 ft.

The course, which was practically level, was laid off with chain and transit, and for the first 500 ft. stations were established every 50 ft., and after that, every 100 ft. The method of making the test was as follows:

With the headlight in operation and directed along the course in such a manner that the nearer edge of the reflected beam first touched the ground at about 400 ft. in front of the lamp, the photometer was set up over each station in turn, with its tube directed toward the headlight. The comparison lamp, held by one person, who also held at the lamp one end of a 100-ft. steel tape, was moved at the will of the observer at the sight box until a photometric balance was obtained. Several observations were made at each station by different observers, which on account of fluctuations in the source of light, at times varied considerably. The values of illumination presented in Table II represent the average of these readings.

The variation of headlight illumination with distance as determined in this test is clearly shown in Table II as well as in Figs. 8 and 9 whose curves are plotted from the data in the above table. Fig. 8 is plotted to a larger scale and includes headlights numbered 2, 4 and 7 which showed the greatest intensities. It should be noted that there is a marked similarity in the general form of these three curves and the relative intensities of the illumination in spite of the fact that they are taken from different types of headlights. In Fig. 9, the intensities of the remainder of the headlights are shown together with a portion of the curves reproduced from Fig. 8 to smaller scale. From this one figure, therefore, a comparison can be made of the intensities of all types and makes of headlights tested. The contrast between curve No. 5 representing the common type of kerosene oil locomotive headlight and the other curves, representing more powerful types, is very marked, and it is interesting to note that at the maximum distance of 1,300 ft. considered in these tests, three headlights, numbered 2, 4 and 7 gave an illumination considerably above the maximum possible at any distance with the kerosene oil headlight.

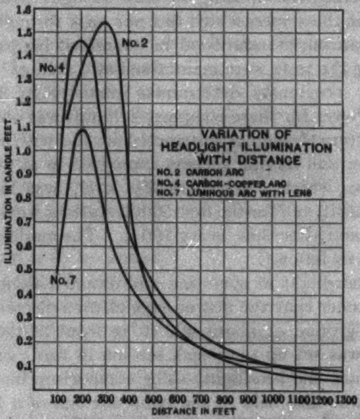

FIG. 8

It will be noted from the curves, Fig. 8 and 9, that in nearly all cases the illumination starting at some value near the lamp increased to a maximum at from 200 to 400 ft. from the lamp, and again decreased as the distance was increased.

That the point of maximum intensity is at some distance from the lamp may be accounted for from the fact that at distances less than that at which the maximum occurs, the illumination is largely due to the direct and not the reflected rays. At points

TABLE I. ILLUMI

Headlight	Volts	Amperes	Intensity							
			Above					Below		
			75 deg.	60 deg.	45 deg.	30 deg.	15 deg.	0 deg.	15 deg.	30 deg.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
No. 1	550	4.5	—	—	180.5	29.3	460	467.5	426	504
No. 2	550	4.38	14.7	91.6	93.2	120	70.8	103.2	246	398
No. 2 Corrected	550	4.38	19.7	123.3	125.5	141.5	95.3	139.2	332	537
No. 3	550	4.32	—	—	—	758	696	760	723	690
No. 3 Reversed	550	2.95	—	—	26.9	44.5	77.5	35.7	47.8	53.5
No. 4	33	27.9	32.6	51	181.8	330	865	1100	925	1423
No. 5	—	—	12.7	19	21.9	23.4	23.6	18.9	15.2	12.3
No 5 (Low)	—	—	—	—	—	—	—	—	—	—
No. 6	—	—	36.3	36.9	36.3	37.9	36.1	35.9	35.8	35.5
No. 7	550	4.59	—	—	—	—	—	—	—	—

TABLE II. IL

Headlight	Volts	Ampere	50	100	150	200	250	300
No. 1	550	4.50	—	0.252	—	0.234		0.195
No. 1 Incandescent	550	0.55	0.0231	0.00662	—	—		
No. 2	550	4.38	—	1.15	—	1.11		1.54
No. 2 Incandescent	550	0.50	0.008	0.0019	—	—		
No. 3	550	4.25	—	0.377	—	0.265		0.191
No. 3 Reversed	550	2.93	0.150	0.0173	0.0298	0.0196		0.042
No. 4	33	27.90	—	0.801	—	1.46		0.658
No. 5	—	—	0.0274	0.0175	0.0158	0.0090	0.0746	0.0533
No. 6	—	—	—	0.0315	—	0.0613		0.0627
No. 7	550	4.59	—	0.485	—	1.09		0.604

UX TESTS OF HEADLIGHTS

	Mean spherical candle power	Illumination corresponding to m.s.c.p. (14) / $(25.7)^2$	Illumination at 25.7 ft. (candle feet)			Ratio of illumination to illumination of oil lamp	Per cent deviation (17) from (18)	Per cent deviation (16) from (18)	Multiplying factor Ratio of (18) to (15)
5 deg.			Max.	Min.	Avg.				
(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
[illegible]	322.5	0.497	87.5	20.9	45.5	23	54.1	92.5	91.8
16.4	185	0.281	125.7	45.3	93.2	48.2	51.5	32.4	332
22.1	255	0.387	—	—	93.2	—	—	—	241
—	597.5	0.906	110.5	40.2	71.5	36.9	43.8	55	70
—	43.5	0.066	13.8	3.8	8.7	4.5	56.5	58.3	131.5
[illegible]	790	1.197	147	36.4	70.2	36.2	48.2	109	58.7
—	16.35	0.025	2.1	1.79	1.94	1	8.5	8.3	77.5
—	—	—	1.3	1.13	1.21	—	—	—	—
[illegible]	34.9	0.053	8.16	7.53	7.83	4.04	3.8	4.2	147.5
—	—	—	168	34.5	95	49	63.7	77	191.5

ANDLE-FEET

600	700	800	900	1000	1100	1200	1300
0.0585	0.0221						
0.279	0.145	0.175	0.117	0.0804	0.047	0.0511	0.0446
0.082	0.075	0.0595	0.045	0.034	0.030	0.0153	0.0103
0.0116	0.00947	0.00429	—	—	—	—	—
0.395	0.265	0.129	0.150	0.104	0.0703	0.090	0.0716
0.000779	—						
0.0222	0.192	0.147	0.118	0.00925	0.00804	0.00727	0.00639
0.236	0.141	0.143	0.151	0.101	0.110	0.0944	0.0871

which are illuminated by both direct and reflected rays, the illumination is naturally higher.

Test No. 18. *A Spectrophotometric Analysis of the Light from Each Lamp.*

In order to determine the relative intensities of the various primary colors in the direct rays of the several types of head-

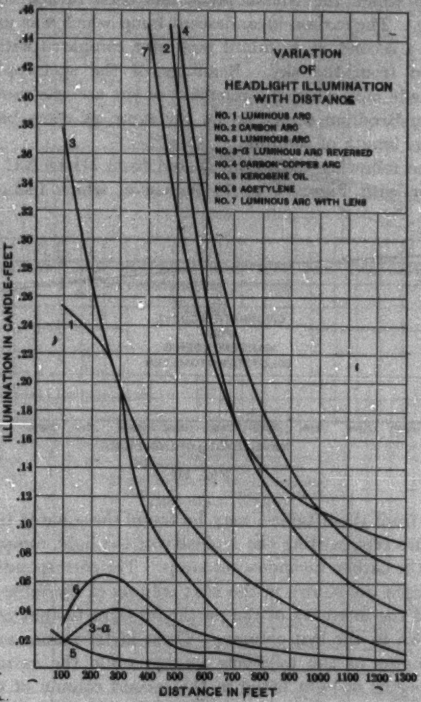

FIG. 9

lights, a Martens-Koenig spectrophotometer was used. With this instrument the intensity of the light in the yellow portion of the spectrum, corresponding to the wave length of sodium light, (0.0005890 cm.) was balanced against that in the same portion of the spectrum furnished by a carbon incandescent lamp operating at constant rated voltage. The ratio of intensities in other portions of the spectrum was then obtained by turning the Nichol prism of the instrument through a measurable angle, thus polarizing a portion of the light from one of the sources. This ratio is then proportional to the square of the tangent of the angle from the point of complete polarization through which the Nichol prism has been turned to obtain a balance. The carbon incandescent lamp which was used in this case as a secondary standard was later compared with daylight reflected from the sky. Readings of the spectrophotometer were made only when the intensity of the arc was shown by the Lummer-Brodhun screen to be the same as when balanced at the wave length of sodium.

In the following tables, numbered from III to XII inclusive, together with Figs. 11 to 14 inclusive, which include curves plotted from these tables, may be found the squared tangents of the angles representing the intensity of the light compared with that of the carbon incandescent lamp. The corresponding values for daylight are shown in the next column of the table while the ratios of the intensity of the particular light to that of daylight are shown in the last column. These latter values are plotted as ordinates in the following curves while the corresponding wave lengths of light listed in the second column of the tables are plotted as abscissæ.

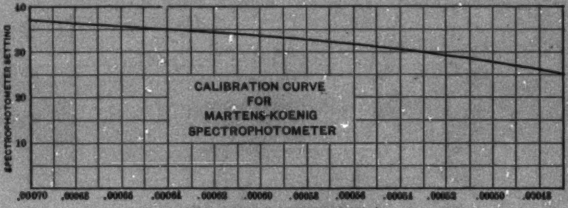

FIG. 10

In further explanation of the curves given in Fig. 11 to 15 inclusive, it should be noted that in each figure curve *D* represents the ratio of intensity of the carbon incandescent lamp to daylight. It is possible, therefore, to compare the spectral intensities of the lights being considered, with daylight not only, but also with the incandescent secondary standard lamp.

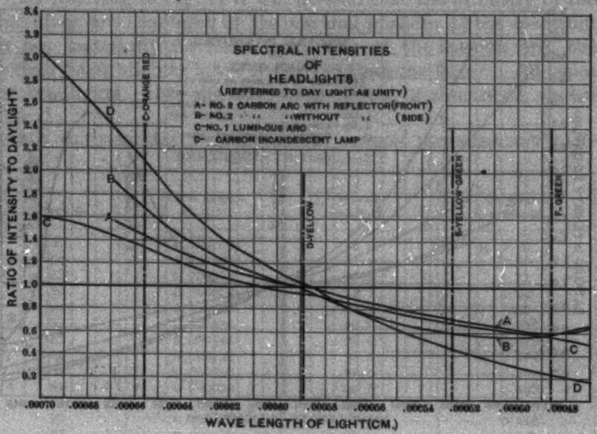
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFFERRED TO DAY LIGHT AS UNITY)
A- NO. 2 CARBON ARC WITH REFLECTOR (FRONT)
B- NO. 2 " " WITHOUT " (SIDE)
C- NO. 1 LUMINOUS ARC
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
C-ORANGE RED
D-YELLOW
E-YELLOW-GREEN
F-GREEN
A
B
C
D
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (CM.)

FIG. 11

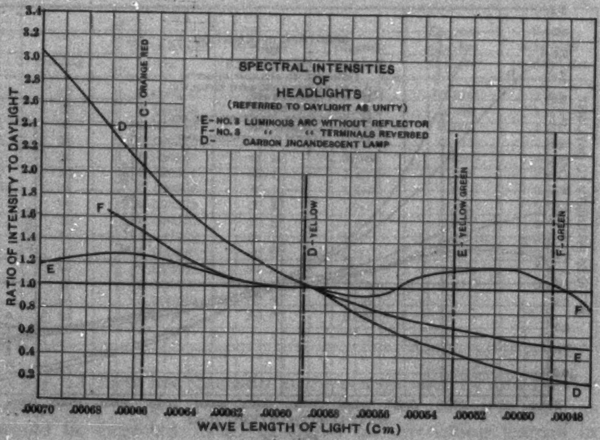
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
E- NO. 3 LUMINOUS ARC WITHOUT REFLECTOR
F- NO. 3 " " TERMINALS REVERSED
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
C - ORANGE RED
D - YELLOW
E - YELLOW GREEN
F - GREEN
D
E
F
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)

FIG. 12

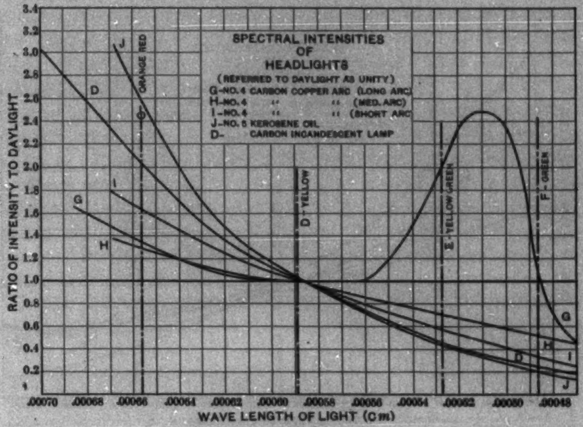
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
G-NO. 4 CARBON COPPER ARC (LONG ARC)
H-NO. 4 " " (MED. ARC)
I-NO. 4 " " (SHORT ARC)
J-NO. 5 KEROSENE OIL
D- CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)
C - ORANGE RED
D - YELLOW
E - YELLOW GREEN
F - GREEN
D
J
I
G
H
D
G
H
I
J

FIG. 13

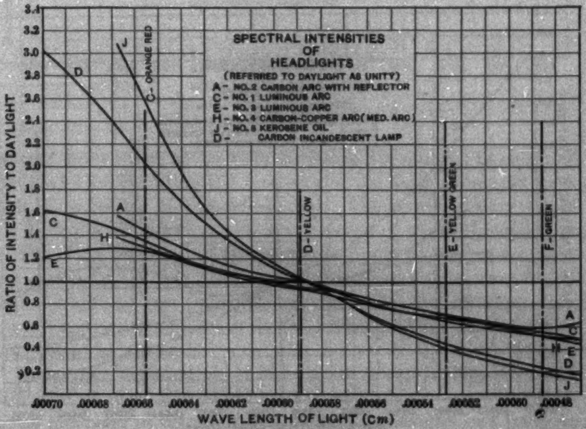
SPECTRAL INTENSITIES
OF
HEADLIGHTS
(REFERRED TO DAYLIGHT AS UNITY)
A - NO. 2 CARBON ARC WITH REFLECTOR
C - NO. 1 LUMINOUS ARC
E - NO. 3 LUMINOUS ARC
H - NO. 4 CARBON-COPPER ARC (MED. ARC)
J - NO. 5 KEROSENE OIL
D - CARBON INCANDESCENT LAMP
RATIO OF INTENSITY TO DAYLIGHT
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
.00070
.00068
.00066
.00064
.00062
.00060
.00058
.00056
.00054
.00052
.00050
.00048
WAVE LENGTH OF LIGHT (Cm)
C - ORANGE RED
D - YELLOW
E - YELLOW GREEN
F - GREEN
D
J
C
A
H
E
A
C
H
E
D
J

FIG. 14

By referring to Fig. 11 it will be seen that the intensity of the luminous arc headlight in the various portions of the spectrum is not materially different from that of the carbon arc, the former being slightly lower in the red than the latter. All types of headlights, with the exception of the kerosene oil shown in Fig. 13, have less intensity in the orange and red and greater intensity in the green and violet than the incandescent lamp, as would be expected. Fig. 12 shows an interesting feature in connection with the luminous arc headlight with terminals reversed which provision is made in some cases for temporarily

TABLE III. SPECTRAL INTENSITIES OF CARBON INCANDESCENT LAMP REFERRED TO DAYLIGHT

Setting	Wave length (mm.)	Average reading	Cotangent squared
37	0.000700	29.8	3.04
36	0.000668	33.1	2.36
35	0.000640	37.4	1.71
34	0.000812	41.7	1.26
33	0.000586	45.1	1.00
32	0.000564	49.0	0.758
31	0.000548	52.0	0.610
30	0.000532	55.0	0.494
29	0.000516	58.0	0.393
28	0.000502	60.5	0.322
27	0.000490	63.0	0.260
26	0.000480	65.0	0.218
25	0.000470	67.0	0.182

TABLE IV. SPECTRAL INTENSITIES OF HEADLIGHT NO. 1

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	36.1	0.530	0.329	1.61
36	0.000668	38.1	0.613	0.425	1.44
35	0.000640	40.1	0.710	0.585	1.21
34	0.000812	42.1	0.815	0.795	1.02
33	0.000586	44.1	0.935	1.00	0.935
32	0.000564	46.1	1.075	1.32	0.815
31	0.000548	48.1	1.240	1.64	0.755
30	0.000532	50.1	1.42	2.03	0.700
29	0.000516	52.1	1.65	2.55	0.646
28	0.000502	54.1	1.90	3.11	0.610
27	0.000490	56.0	2.21	3.85	0.574
26	0.000480	57.8	2.51	4.60	0.545
25	0.000470	58.9	2.74	5.51	0.497
24	0.000460	59.8	2.96		
23	0.000450	60.0	3.22		

reducing the intensity of headlights. Such a reversal introduces a relatively high intensity in the green portion of the spectrum probably due to the burning away of the copper electrode. A similar but more marked effect is shown in Fig. 13 in connection with an arc headlight of another type using a lower electrode of copper, with which it was found that, if a long arc were permitted to form, very high intensities in the green portion of the spectrum were introduced, probably due to the cause mentioned above. From the green appearance of the light given at times by this electric headlight, which was used in the road tests, it is quite probable that this condition sometimes obtains in practice and it is believed that the possibility of obtaining green phantom signals is increased by this fact.

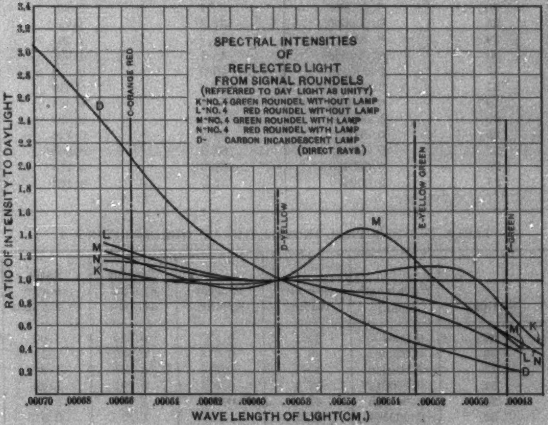

FIG. 15

Test No. 19. A spectrophotometric Analysis of the Light Reflected from Roundels.

In this test the same spectrophotometer was used and the method of procedure was the same as in test No. 18, with the exception that the light analyzed was first reflected from signal roundels. Headlight No. 4, which was used in the road tests, furnished the light for this analysis. Tables XIII to XVI inclusive show the results obtained in this test which are plotted in Fig. 15. The point of particular significance, in explanation of the phantom signals found in the road tests, is the fact that the intensities in the green portion of the spectrum of light reflected from green roundels are much greater than those reflected from red roundels. It is further noted that the effect of placing an unlighted signal lamp back of the green roundel, as is usually

TABLE V. SPECTRAL INTENSITIES OF HEADLIGHT NO. 2 FRONT WITH REFLECTOR

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	39.2	0.666	0.425	1.57
35	0.000640	41.1	0.760	0.585	1.30
34	0.000812	43.0	0.870	0.795	1.09
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	47.0	1.142	1.32	0.865
31	0.000548	49.0	1.320	1.64	0.805
30	0.000532	50.8	1.50	2.03	0.740
29	0.000516	52.9	1.745	2.55	0.685
28	0.000502	54.5	1.960	3.11	0.630
27	0.000490	56.7	2.31	3.85	0.600
26	0.000480	59.0	2.76	4.60	0.600
25	0.000470	62.0	3.54	5.51	0.641
24	0.000460	66.0	5.05	—	—
23	0.000450	71.1	8.50	—	—

TABLE VI. SPECTRAL INTENSITIES OF HEADLIGHT NO. 2 TURNED SIDEWISE NO REFLECTOR

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	42.0	0.810	0.425	1.91
35	0.000640	42.6	0.840	0.585	1.44
34	0.000812	43.5	0.900	0.795	1.13
33	0.000586	44.2	0.944	1.00	0.944
32	0.000564	45.3	1.020	1.32	0.773
31	0.000548	46.5	1.11	1.64	0.677
30	0.000532	48.4	1.26	2.03	0.620
29	0.000516	50.5	1.47	2.55	0.576
28	0.000502	53.0	1.75	3.11	0.563
27	0.000490	56.0	2.20	3.85	0.570
26	0.000480	59.3	2.83	4.60	0.615
25	0.000470	62.0	3.53	5.51	0.640
24	0.000460	63.9	4.15	—	—
23	0.000450	64.6	4.42	—	—

TABLE VII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 3

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	32.0	0.390	0.329	1.19
36	0.000668	36.3	0.540	0.425	1.27
35	0.000640	39.8	0.691	0.585	1.18
34	0.000812	42.4	0.830	0.795	1.04
33	0.000586	44.8	0.985	1.00	0.985
32	0.000564	46.4	1.10	1.32	0.834
31	0.000548	48.0	1.23	1.64	0.750
30	0.000532	49.9	1.40	2.03	0.690
29	0.000516	51.5	1.57	2.55	0.616
28	0.000502	53.2	1.78	3.11	0.572
27	0.000490	55.0	2.03	3.85	0.527
26	0.000480	56.9	2.35	4.60	0.510
25	0.000470	58.7	2.70	5.51	0.490
24	0.000460	60.3	3.07	—	—
23	0.000450	62.0	3.53	—	—

TABLE VIII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 3 TERMINALS REVERSED

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	39.9	0.836	0.425	1.65
35	0.000640	41.0	0.869	0.585	1.28
34	0.000812	42.5	0.916	0.795	1.055
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	48.3	1.122	1.32	0.955
31	0.000548	53.0	1.327	1.64	1.068
30	0.000532	57.0	1.540	2.03	1.16
29	0.000516	60.0	1.732	2.55	1.175
28	0.000502	62.5	1.921	3.11	1.185
27	0.000490	64.0	2.050	3.85	1.09
26	0.000480	65.0	2.144	4.60	1.00
25	0.000470	65.0	2.144	5.51	0.835
24	0.000460	64.5	2.097	—	—

TABLE IX. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4 MEDIUM ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	37.4	0.765	0.425	1.375
35	0.000640	40.0	0.839	0.585	1.20
34	0.000812	42.3	0.910	0.795	1.042
33	0.000586	44.8	0.993	1.00	1.985
32	0.000564	46.9	1.069	1.32	0.864
31	0.000548	49.0	1.150	1.64	0.804
30	0.000532	50.7	1.222	2.03	0.734
29	0.000516	52.4	1.299	2.55	0.658
28	0.000502	54.0	1.376	3.11	0.608
27	0.000490	55.4	1.450	3.85	0.545
26	0.000480	56.8	1.528	4.60	0.504
25	0.000470	57.8	1.588	5.51	0.455
24	0.000460	58.5	1.632	—	—

the case in practice, apparently increases, to a very marked extent, the intensity in the yellow-green portion of the spectrum of the reflected light.

Test No. 20. *A Laboratory Determination of the Reflection Coefficients of Roundels with and without Signal Lamps.*

After it was found in the previous test that the placing of a signal lamp back of a green roundel greatly increased the intensity of the reflected light in the yellow-green portion of the spectrum, it seemed worth while to determine the reflection coefficients of both green and red roundels with and without signal lamps placed directly behind them in the position which they occupy in practice. These results are clearly shown in Table XVII from which it will be noted that the reflection coefficients of red roundels are slightly greater than those of green roundels but that in both cases, the coefficients are greater when the roundels are mounted in front of signal lamps. It seems probable that the increase in this coefficient is due to the presence of the lens of the signal lamp.

TABLE X. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4. LONG ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	37.5	0.588	0.329	1.79
36	0.000668	38.3	0.623	0.425	1.47
35	0.000640	39.9	0.700	0.585	1.20
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	49.0	1.32	1.32	1.00
31	0.000548	55.2	2.06	1.64	1.26
30	0.000532	62.3	3.61	2.03	1.78
29	0.000516	68.2	6.25	2.55	2.46
28	0.000502	70.0	7.51	3.11	2.42
27	0.000490	68.0	6.10	3.85	1.58
26	0.000480	61.4	3.35	4.60	0.728
25	0.000470	58.1	2.57	5.51	0.465
24	0.000460	58.2	2.60	—	—

In conclusion, it may be well to call attention to other tests not formally listed herein, which were made in connection with the laboratory tests to reproduce, if possible, the phantom signals noticed in the road tests. Headlight No. 4 was mounted upon the platform described in test No. 17, and red and green signal roundels with and without signal lamps were placed in a position corresponding to that of the home signal. Although the signal lamps located behind the roundels being tested were not lighted, yellowish green reflections were obtained from the roundels which were quite as brilliant as other signals placed near by for comparison, and might have been easily mistaken for a green signal.

TABLE XI. SPECTRAL INTENSITIES OF HEADLIGHT NO. 4. SHORT ARC

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	41.1	0.760	0.425	1.79
35	0.000640	42.6	0.841	0.585	1.44
34	0.000812	43.9	0.921	0.795	1.16
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	46.1	1.075	1.32	0.815
31	0.000548	47.1	1.155	1.64	0.705
30	0.000532	48.0	1.230	2.03	0.606
29	0.000516	48.9	1.305	2.55	0.512
28	0.000502	49.2	1.335	3.11	0.429
27	0.000490	49.6	1.380	3.85	0.358
26	0.000480	49.8	1.400	4.60	0.304
25	0.000470	49.95	1.42	5.51	0.258
24	0.000460	50.0	1.42	—	—
23	0.000450	50.0	1.42	—	—

TABLE XII. SPECTRAL INTENSITIES OF HEADLIGHT NO. 5

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
37	0.000700	52.1	1.641	0.320	4.99
36	0.000668	48.9	1.31	0.425	3.08
35	0.000640	46.9	1.14	0.585	1.95
34	0.000812	45.8	1.055	0.795	1.33
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	44.7	0.980	1.32	0.742
31	0.000548	44.3	0.950	1.64	0.580
30	0.000532	44.0	0.930	2.03	0.459
29	0.000516	43.8	0.918	2.55	0.361
28	0.000502	43.3	0.858	3.11	0.276
27	0.000490	42.8	0.855	3.85	0.222
26	0.000480	42.0	0.810	4.60	0.176
25	0.000470	40.7	0.739	5.51	0.134
24	0.000460	38.6	0.635	—	—

It is believed the results of the laboratory tests will be of interest from the photometric standpoint and that some pe-

TABLE XIII. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A GREEN ROUNDEL WITHOUT LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	34.3	0.465	0.425	1.09
35	0.000640	37.4	0.585	0.585	1.00
34	0.000812	41.1	0.760	0.795	0.955
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	49.6	1.38	1.32	1.05
31	0.000548	52.7	1.72	1.64	1.05
30	0.000532	56.2	2.22	2.03	1.09
29	0.000516	59.3	2.83	2.55	1.11
28	0.000502	61.0	3.25	3.11	1.04
27	0.000490	60.9	3.21	3.85	0.835
26	0.000480	59.4	2.85	4.60	0.62
25	0.000470	57.7	2.50	5.51	4.54
24	0.000460	—	—	—	—

TABLE XIV. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A RED ROUNDEL WITHOUT LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	36.9	0.562	0.425	1.32
35	0.000640	39.4	0.671	0.585	1.15
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.00	1.00	1.00
32	0.000564	47.8	1.21	1.32	0.916
31	0.000548	50.5	1.47	1.64	0.896
30	0.000532	53.0	1.75	2.03	0.862
29	0.000516	55.0	2.03	2.55	0.795
28	0.000502	56.8	2.33	3.11	0.750
27	0.000490	56.3	2.24	3.85	0.582
26	0.000480	55.8	2.16	4.60	0.470
25	0.000470	54.5	1.96	5.51	0.356

TABLE XV. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A GREEN ROUNDEL WITH LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	36.0	0.529	0.425	1.25
35	0.000640	38.3	0.622	0.585	1.06
34	0.000812	40.8	0.745	0.795	0.936
33	0.000586	45.5	1.03	1.00	1.03
32	0.000564	53.3	1.79	1.32	1.36
31	0.000548	57.0	2.36	1.64	1.44
30	0.000532	58.0	2.55	2.03	1.26
29	0.000516	57.5	2.46	2.55	0.965
28	0.000502	56.8	2.33	3.11	0.75
27	0.000490	55.8	2.16	3.85	0.561
26	0.000480	54.1	1.90	4.60	0.413

culiarities noted in the use of powerful headlights in railroad operation are explained thereby.

CONCLUSIONS

As a summary of the results, the following may be noted:

First. That the magnitude of the illumination is a function not only of the total light flux emitted from the lamp, but also its distribution.

TABLE XVI. SPECTRAL INTENSITIES OF REFLECTED LIGHT FROM A RED ROUNDEL WITH LAMP

Setting	Wave length (mm.)	Average reading	Tangent squared	Tangent squared daylight	Ratio intensity to daylight
36	0.000668	35.1	0.494	0.425	1.16
35	0.000640	38.9	0.650	0.585	1.11
34	0.000812	42.0	0.810	0.795	1.02
33	0.000586	45.0	1.000	1.00	1.00
32	0.000564	47.3	1.170	1.32	0.886
31	0.000548	49.5	1.370	1.64	0.835
30	0.000532	51.3	1.55	2.03	0.763
29	0.000516	52.5	1.69	2.55	0.663
28	0.000502	53.0	1.75	3.11	0.563
27	0.000490	52.9	1.74	3.85	0.451
26	0.000480	52.5	1.70	4.60	3.70

TABLE XVII. REFLECTION COEFFICIENTS OF ROUNDELS

Angle deg.	Green	Green with lens	Red	Red with lens
7½	0.0418	0.0478	0.05	0.0512
15	0.0375	0.0437	0.048	0.0514
22½	0.0352	0.0468	0.0486	0.0505
30	0.0413	0.0459	0.0467	0.0453

Second. That that reflector in which the largest proportion of total light flux falls in the vertex will have the highest multiplying factor.

Third. That the lens type of projector has a higher multiplying factor than the reflector type, other things being equal.

Fourth. That the spectral intensities of the luminous arc headlights are not noticeably different from those of the carbon arc, although the former are slightly lower in the red portion of the spectrum than the latter.

Fifth. That headlight No. 4 having a lower electrode of copper may so operate in practice as to produce relatively high intensities in the yellow-green portion of the spectrum. This is also true of headlight No. 3 with terminals reversed.

Sixth. That oil headlight No. 5 gives intensities higher in the red and lower in the green than all other headlights tested.

Seventh. That the reflected light from green roundels has a higher intensity in the green than that from red roundels and that this intensity is greatly augmented when a signal lamp is placed behind the roundel as in practice.

In closing this paper it is desired to acknowledge the very great assistance furnished the authors by their associates in the University.

DISCUSSION ON "HEADLIGHT TESTS." JEFFERSON, N. H., JUNE 28, 1910.

C. A. B. Halvorson, Jr.: There are a few points to which I would call attention.

So far as I am able to judge, the benefit to be derived from the use of a powerful headlight is the feeling of security and confidence given to the engineer. With the track ahead in darkness or poorly illuminated, his nerves may be kept constantly "on edge" making him liable to blunders. Or, on the other hand, he may become reckless and simply trust to luck. I base my opinion on experience gained under actual operating conditions and from talks with engineers.

No reference is made to tests on wet or foggy nights. On such nights the ground and the sleepers as well as all other unpainted wooden objects along side the track appear black from absorption of water. Or, in case of a heavy fog bank this will appear as a solid illuminated wall shutting out the view of anything ahead.

There is another point in the conclusions to which I wish to refer. It is stated that "A powerful opposing headlight adjacent to block signals so obscures the latter as to make it difficult to read them correctly at distances exceeding 1,000 ft." It seems to me that this would be easily overcome by drawing up a set of rules governing the use of headlights. This has been done on some roads. When two approaching trains come within view of one another, the luminous arc of both headlights are extinguished and the less powerful incandescent lamps lighted. This practice obviates the difficulties mentioned.

Instead of advocating less powerful headlights, I would recommend increasing the efficiency by raising the current to 7 amperes. The ordinary luminous headlight as operated to-day is run at 4 amperes, consuming about 500 watts at the terminals. Improvement in the accuracy of the mirrors is also needed.

It was my pleasure to make a test on the D. & H. line between Albany and Whitehall, using a locomotive headlight operating with a 7-ampere magnetite arc, and we could easily discern persons walking on the track at a distance of 1700 ft. A combination of mirrors was used in this headlight, consisting of a large parabolic metallic mirror and a 9-in. Mangin mirror. The results obtained with this headlight were very fine, indeed.

With reference to reversing the polarity of the arc in order to dim the light, I would suggest that an ordinary incandescent lamp would probably give much better results than a reversed arc. Such a lamp placed out of focus of the mirror as an auxiliary to the luminous arc seems to me the best solution of the glare trouble.

Most of you are probably familiar with the luminous arc. It is a very long arc and the light is given from a core which is intensely bright. When a Mangin mirror is used, the light projected is practically an image of the arc. The beam, therefore, will be of small width, the principal extension being in a vertical plane. By using small diameter electrodes it should be possible to confine the light to the space between the rails. and this has actually been accomplished. In this way all trouble on account of reflection from roundels, etc., can be eliminated.

The third conclusion states that " The lens type of projector has a higher multiplying factor than the reflector type, other things being equal ". This may be true when the comparison is made with ordinary metallic mirrors. Comparing the lens form with the Mangin mirror form of headlight I doubt that the statement holds good. I would like to know whether Professor Harding has made any tests along these lines.

John B. Taylor: Some data as to the make-up of the observing committee seems desirable; first, whether the same eleven men were interested in all the tests, and, second, whether they were trained railroad men, and if not, what was their particular occupation in life. I understand tests will show about one man out of every two dozen to be color blind, so that we should know whether all these men went through a color blind examination, before they were given a position of this committee. I would ask also whether the lower values of distances given for recognizing the signals and obstructions were usually determined by one or two exceptional men, or whether they are fair low average values?

George H. Stickney: The brief inspection which I have made of the paper seems to indicate that, under existing conditions of signals, etc., the use of high power headlights was not found beneficial, inasmuch as they interferred with the reading of signals.

The purpose of the headlight is two-fold, namely to assist the engineer in seeing ahead, and to warn people of the approach of the train. With low-power headlights the former function is practically lost, and in foggy weather the range of warning is quite limited. For these purposes therefore there is unquestionably a demand for powerful headlights.

The objection to their use apparently relates entirely to the reading of signals. In regard to this point there seem to be a number of possibilities of eliminating or reducing such interference. For example, the headlight beam may be directed very slightly downward so as to fall below the eyes of the engineer of an approaching locomotive. At the same time the signals could be placed above the range of the beam. Very accurate control of a light beam is obtained, for instance, in a stereopticon projector, so that it would seem possible to produce this effect without limiting the range of illumination along the track.

Harry Barker: The opening paragraph of the paper states that the Indiana Railroad Commission was instructed to investigate the rules regarding the compulsory use of more powerful headlights on steam locomotives operating in the State of Indiana. I would ask if Professor Harding could inform us as to the ruling of the Commission? I understand, that in spite of Professor Benjamin's report, mentioned later in Professor Harding's paper, and in spite of the somewhat adverse findings of the special sub-commission, or of the individuals of the Railroad Commission, the Commission has, nevertheless, ordered that high-power lamps be used. If that is so, it might be interesting to know some of the qualifications of these instructions.

C. P. Steinmetz: This paper is very interesting, though some of the results at first appear unexpected; *i.e.*, the result that the more powerful headlight is inferior, in certain respects, by making the signals less distinguishable. If we apply that reasoning still further, it would follow that the best way would be to have no headlight at all, because then you would see the signals best.

Now, on the other hand, if we have a headlight, and need a headlight, it appears reasonable to expect that the more powerful the headlight is, the further distance we can see obstructions or other defects of the roadbed, and the further distance one can be seen; therefore, the most powerful headlight would be the most satisfactory one, except as regards the signals. It would be interesting to investigate whether this objection regarding signals could not be overcome by applying the same remedy. If we need a high-power headlight, why not also use higher powered signal lights to make the two again comparable with each other, and at the same time apply this remedy which has been suggested here, that is, to control the beam of the headlight so as not to throw it directly on the signals.

We all know if we send a powerful beam of a searchlight against a small and low intensity light, we do not see the latter light very well, and we do not need any test to tell us this. Besides, it appears to me that the case of looking at signal lights against an opposing headlight is rather an exceptional case. If there is another train coming, with a powerful light, either we must be sure of our signals, or must slow down. I do not think it is generally the case that two locomotives, when not certain of their signals, will approach each other at full speed. We may turn the headlight away, or turn it out, or do anything else, or may slow down, and if we slow down even for a distance of a few hundred yards, that distance will be sufficient to enable us to avoid any obstruction.

I believe the question requires further consideration and investigation before we can accept the theory that the headlight of a train can be too powerful.

Charles F. Scott: One use of the headlight referred to a few moments ago is to give a warning of approaching trains to people not connected with the railroad. In some cases, the headlight can be seen long before the approach of the car can be heard.

As electric trains come into use, and do not have smoke to indicate their presence at a long distance, the headlight at night gives a very fair indication of the position of distant trains, which would be of very great use on single track roads.

With regard to seeing of signals, the suggestion is made that a different form of signal, a position signal, might be advantageous instead of a colored signal. A position signal might be seen very clearly, irrespective of the color of the signal.

With regard to operation at full speed, and in connection with a point made by the last speaker, namely, the suggestion that if there is an approaching train with a powerful headlight, it is well to slow down, it may be remarked that there are cases, such as on double track roads, or four track roads, with block signals placed at frequent intervals, in which trains do run in opposite directions at high speeds, with signals at frequent intervals where the approaching headlights may dazzle the eyes of the engineer.

All these little points show the intricacy of the problem, and I think the paper, as a whole, brings out in a very emphatic way the need for the kind of investigation and scientific analysis which has been given to a problem of this kind. I presume that practically all of us, would have said off hand that the arc light would be an excellent headlight and its general adoption desirable. But these various indirect points, the dazzling of the eye of the approaching engineer, the obscuring of signals, the changing of the colors of signals by reflected light, all of which indicate the importance of a thorough scientific investigation of the subject, show the high value of papers such as the one we have just had.

George A. Hoadley: There is just one point not touched on, and that is this; the very great difficulty there is of forming any judgment, within satisfactory bounds of accuracy, as to the distance of a powerful headlight. To a person on the track, it is impossible to tell if the headlight is three hundred yards away, or one hundred feet, so it seems to me the headlight which gives a perfectly parallel beam of light, that does not strike the track, is an objectionable form of headlight. If the light strikes the track, the observer has an opportunity to determine the distance of the headlight from the point at which he is standing.

Harry P. Wood: I would ask Professor Harding if he made any test to determine the proper height of a headlight above the track? In the electric road the headlight is close to the track, and I understand, as regards engineers in the cab of a locomotive, there is a difference of opinion as to whether the headlight should be at the center of the smoke-box or above the smoke-box. I think the lower headlight will be better than the headlight which is placed higher up, as in the lower position the beam of light will not be entirely in the direction of the engineer's vision.

J. C. Lincoln: I should like to know if Professor Harding made any test to determine whether the green reflection, which seemed to throw some doubt on the signals, could be gotten rid of by the suggestion just made, of throwing the light on the truck, so that no direct light from the headlight would strike the signal whatever?

C. Francis Harding: This subject of compulsory use of more powerful headlights on railroads, especially on steam railroads, is a comparatively live one in the middle west at the present time. Because of the fact that it has been given especial attention in that section of the country, and for the reason that it has been thought that engineers in general and especially those connected with steam railroad work, would be interested in this discussion, it is presented in this form to-day.

Referring to the question of the feeling of the engineer on the engine, I would say that all of the signal engineers with whom I have talked, and also many of the older steam locomotive engineers, have expressed themselves emphatically in favor of the old type of headlight, so far as security is concerned, and in fact some of the older engineers who made up the Committee of the Brotherhood of Locomotive Engineers, who first proposed this bill to the Indiana Legislature, told me that they could run equally well without any headlight at all, that they did not depend upon the aid of a headlight for determining their location or determining the schedule time in passing various objects —that they had markers of their own along the track, such as houses, gate openings, bridges, etc., and that they could easily get this information without any headlight, in a manner that was entirely satisfactory to them.

Regarding the question of fogs, I will say that some of the night tests at the University were carried out during foggy nights, and when we have a bank of fog in front of the headlight, looking parallel with the track, we have in front of us practically an opaque screen, brilliantly lighted, but very near the headlight, through which it is almost impossible to see, and that opaque screen seems to be more of a barrier, the greater the intensity of the light.

With regard to the matter of extinguishing or reducing the intensity of the lights in approaching other locomotives, I will say that, of course, that practice is used with interurban cars to a large extent, and it is probably a practical suggestion in the case of a good many steam roads, but an objection to that has been brought up by one of the signal engineers of a road entering Chicago. He says that an engineer on a train entering Chicago at the schedule speed has to read a signal every fifty-five seconds, and it would be impossible to diminish the intensity of the light, momentarily, while reading signals—it would therefore be necessary to reduce the light during the entire run.

Regarding the picking up of objects other than those considered in this test—the various observers on the road test in going from Indianapolis out to the scene of the test, were able by counting the poles to pick up overhead bridges, fences, etc., at a maximum distance of a quarter of a mile. All of these objects were white, or nearly so, and it was remarkable to note the difference in distance in picking up objects which were light and those which were dark. It happened that all the objects used in the test were dark, or nearly black, and it was surprising to all observers to note the results shown in the tests, that we could run down within a very few hundred feet of a black object and not detect it even with a powerful headlight.

I will say that the Mangin mirror type of reflector for headlights was not tested, and the statement in the conclusion of the paper simply applies to the particular lights tested, one with a lens and the other with a reflector, the other features of the light being identical.

Regarding the make-up of the observing committee, I will say that the Railroad Commission was represented by three men, the railroads of the State by three men, the University by three men, and two other parties selected at random. The men were not tested for color blindness, but the comparisons of the results of the different individual papers recorded independently would seem to show that no such condition existed in the eleven observers selected—that none of the members of the observing committee were color blind. I think an inspection of the original data would convince one of that fact. The readings at lower values, *i.e.*, shorter distances, seem to be pretty general, that is, not always noted by the same individuals with an opposing electric headlight while with an opposing oil headlight there is considerable similarity in observations of a single individual with respect to distance.

With regard to the matter of focussing below signals, or opposing engineers, it would seem to the speaker that this must limit the distance at which the headlight can be of use, unless the headlight is to be placed very low on the locomotive. If I understand the suggestion correctly, if we are to limit the height of the beam at a given point below the signal, or below the engineer's eyes on the approaching locomotive, then we must limit the distance that that beam will be spread out longitudinally along the track or else we must lower the headlight to a point below its usual position.

At this point I might take up the question of the placing of the headlight on the locomotive. These locomotive headlights were all tested in the position in which they are used by the Big Four Railroad, namely, just in front of the stack on top of the boiler. Some of the roads use the headlight in front of the boiler, and on a level with the center of same. The interurban headlights tested were used in the position in which they are located on the interurban cars, about four or five feet above the track.

The only objection that I have heard to the mounting of the headlight below the top of the boiler front, is that sometimes it is of advantage for the dispatcher in the stations along the line to detect the number of the locomotive, and this number is often placed in front of, or at the side of the headlight. The zone, and therefore the time, in which the dispatcher is permitted to note the number on high speed trains, is obviously greatly limited if that headlight is placed in front of the boiler. This position also, of course, involves limiting the distance of the illumination in front of the locomotive, unless the headlight is tilted upward.

With regard to the inquiry as to the ruling of the Commission, I will say that the Brotherhood of Locomotive Engineers first proposed the bill, including a minimum of 2,000 candle-power for headlights. Later these tests were made and a report was sent to the Commission. The conclusion of the report, in a nutshell was that the committee felt that a happy medium could be reached in a headlight more powerful than the present headlight, and of proper spectral qualities, which would enable objects to be detected at a greater distance than the present headlight, but not sufficiently powerful to interfere with signals. The Commission interpreted this statement as an argument in favor of reducing the candle-power of the headlight and changed the ruling from 2000 to 1500 candle-power, although I think that no one knows what the 1500 means, as it does not state whether it is with or without the reflector. Since the illumination does not follow the inverse square law the ruling should apply to the illumination in candle feet at specified distances in front of the headlight when equipped with a reflector.

The ruling of the Commission is that all of the roads in Indiana, beginning with one third of their equipment in July, 1910, one third in January, 1911 and one third in July, 1911 shall equip their locomotives with headlights having a minimum of 1500 candle-power.

In regard to the advantages of a more powerful headlight in detecting obstructions on the track, I will say that it is, of course, obvious that the more powerful the headlight, the greater the distance at which the objects can be distinguished but it was the feeling of the Committee that the detecting of obstructions on the track was a minor consideration when compared with the correct reading of signals.

With regard to slowing down to read signals, or after detecting objects on the track, I might illustrate my point by referring to the statement of one of the locomotive engineers when called upon by an officer of the road for certain information. The officer asked the engineer what he would do, when running seventy miles an hour, with a powerful headlight, if he saw an object on the track a quarter of a mile ahead, which would cause an accident if struck by the train. The engineer said that he would not apply the brakes to stop for it. The officer asked him for his reason. The engineer said that if he were to stop for every obstacle that he saw on the track a quarter of a mile away, that he thought might be struck by the locomotive, he would not be able to make the schedule—that he depended upon the object getting off the track, and not upon stopping the train in advance of the object.

With regard to the use of signals other than lights, at night will say that the suggestion has been made that semaphores be used, and the lights on the headlight be dispersed rather than concentrated, so that the position of the semaphores would be seen at night sufficiently well to use them in place of the lights.

The distance of the headlight from the observer and the distance of objects along the track in the rays of the headlight are also important questions, and I am glad that they were brought up. It is surprising how inaccurate the judgment of an experienced railroad man is in determining the distance of an approaching locomotive, or even of objects on the track, as seen in the rays of a powerful headlight. This was tried out unofficially, and guesses anywhere from one hundred to two thousand feet, and sometimes up to a mile, were made of distances of objects in front of the engine, as well as distances in front of approaching locomotives.

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THE MODERN OIL SWITCH WITH SPECIAL REFERENCE TO SYSTEMS OF MODERATE VOLTAGE AND LARGE AMPERE CAPACITY

BY A. R. CHEYNEY

The oil switch has become a fundamental part of all large generating systems, and so well has it fulfilled its function that not only has it superseded practically all other forms of switches for such service at all voltages, but manufacturers unhesitatingly claim that it can be constructed so as to safely open short circuits under the worst possible conditions in systems of unlimited kilowatt capacities, the only limiting condition, of course, being that the consumer be willing to pay for it.

In spite of this assurance, repeated warnings that the present switches are becoming a source of possible danger in the rapidly growing central station systems of our large cities are being heard, although neither manufacturer nor operator has seemingly thus far placed any absolute safety limit on just how large a system the present switch is entirely capable of protecting.

Switches may be divided into three classes, each class being further sub-divided into extra high voltage, moderate voltage and low voltage. The three main classes are based upon the maximum generating capacity that the switch may reasonably be called upon to interrupt. The classification, therefore, becomes in fact switches for small systems, for systems of moderate capacity, and switches for use in systems of the largest size. So long as the operating man does not object, the rating of this latter type of switch will continue to be for systems of "unlimited capacity," as any experimental evidence to the contrary is at the expense of the operating system itself.

It is further manifest that oil switches may be built to safely and continuously carry any current that may be required. The use of the switch as a circuit-breaker is the limiting factor in the case. Every switch thus used must not only be able to safely carry or interrupt the load of its particular section, but it must also be capable of safely and repeatedly interrupting short-circuits under severe conditions, with the whole capacity of the generating, transmission, and receiving systems behind it.

The switch with which this paper is mostly concerned is the type almost universally used in the large generating systems of our cities, where the voltage usually runs from 13,000 to 6,000 volts per phase, and is manufactured in various sizes, the 2,500-volt switch with a capacity up to about 3,000 amperes, the 15,000-volt switch up to 2,000 amperes, and the 35,000-volt switch up to 300 amperes rated capacity. Under these conditions the temperature rise in the oil cylinders or tanks is generally kept as low as possible, 28 deg. cent. being sometimes specified.

The switch of both large and small ampere capacity for extra high potential systems seems to have rapidly made a place for itself in the high-tension transmission systems of the country, and to have been extremely satisfactory in most instances. One 60,000-volt switch, it is claimed, opened twenty-five consecutive short-circuits, with a generating capacity of 10,000 kilowatts, within a space of one-half hour, and although the oil was carbonized to a considerable extent, the switch opened the arc entirely satisfactorily on the last break. In another instance two 60,000-volt breakers which had been in service for three years have opened several hundred short-circuits, many of them severe, without a change of oil. The generous dimensions of these switches are sufficient to show that the design is amply safe with regard to distances between conductors, the manufacturers claiming that they figure on an oil which has dropped in insulation until it may be broken down from 6,000 to 10,000 volts on a 0.2-in. gap between needle points. It is impossible in practice, with systems of this nature, to maintain the oil at an exceedingly high insulating value without a great deal of labor and inconvenience, particularly on account of the moisture that is absorbed from the atmosphere. In these switches for high voltage systems, which are now on the market in capacities up to 400 amperes at 110,000 volts, experience seems to show that a large volume of oil greatly increases the factor of safety. Some manufacturers also claim that in switches of this class a horizontal is superior to a vertical break as the pressure due to the head of the oil above the contacts is more effective in preventing the arc from reaching any large dimensions. Switches with a horizontal break are usually made with a thin knife blade in order that it may cut through the oil with the least disturbance. Judging from the written expressions of the users of these high-tension switches, it is evident that for the conditions under which these switches operate they are giving very satisfactory service.

Until the introduction of the steam turbine with its high rotative speeds and correspondingly low self-induction, the present plunger type of switch seemed to fulfill every expectation in moderate voltage systems of large generating capacity. The enormous growth of connected load and, at the same time, the adoption of the turbine as a prime mover, have brought about conditions unforeseen; and not only has the ability of modern switch construction to safely care for the new conditions been questioned, but experimental evidence would lead to the conclusion that either a new form of switch is urgently needed or else a marked change in switchboard construction and station operation.

The high-power switch for 6,000- to 13,000-volt service has at all times required careful supervision, constant attention to smaller details of its operating mechanism, and periodic tests, in order to ascertain that it was always ready for service. This, of course, is not unreasonable. Heavy short-circuits, however, have frequently demonstrated the fact at the present time in our large stations no circuit-breaker which has once opened under heavy short-circuit conditions is entirely safe to be put back on the line again without a thorough overhauling of contacts, cleaning up of the switch and its compartments, on account of the large amount of oil which has been blown out by the explosive pressure of the arc, and also the refilling of the switch cylinders. It is frequently necessary to insert an entirely new set of contacts and to file down the rod tips. This whole operation involves a period of at least two hours, and if spare feeders are not available may lead to considerable annoyance, while, in any case, it may involve a temporary disablement of a large and important investment in apparatus.

Changes, such as the substitution of steel for brass pots, the addition in some instances of insulating dashers to assist in keeping the oil within the pot and also to facilitate the breaking of an arc, and improved operating mechanism and contacts, cover practically all the main points that have been improved upon, since the introduction of the 8-in. cylinder eight or ten years ago, notwithstanding the enormous increase in maximum short-circuit output of the turbo-generator over that of the engine-driven alternator of equal capacity and the fact that the size of units has increased from 5,000 kw. to 20,000 kw. The substitution of boiler-iron tanks for wooden tanks and the gravity opening, with a means of obtaining a certain forced oil flow across the contacts on opening the switch, are a few of the changes in another type.

The Committee on High Potential Disturbances of the Association of Edison Illuminating Companies, 1909, notes that several of the larger companies are making use of reactances in connection with their turbines. These are installed either in the neutral leads of the turbo-generator or in the phase leads themselves. The reactances also facilitate parallel operation. A committee of the same body during the previous year suggested a limit of 40,000 kilowatts of installed machinery as a maximum generating installation that could be safely protected by a modern switch. As, in several instances, the switch has caused considerable damage, frank discussion in the line of improvement of the switch design is asked for.

As a matter of record, with 15,000 kw. of turbines in service, the latest type of oil switch has been quite recently practically emptied of its oil, the remaining oil being reduced to a state of absolute blackness and the contacts and rods so badly burned that they were unfit for further use without renewing, makes it evident that some change is needed in our present switchboard or switch design.

Modern operation generally calls for the use of a single operating bus-bar for reasons of both reliability and economy. Choke coils to limit the generating capacity in one section of the bus to a value of perhaps 20,000 kw., or a capacity slightly above that quoted when the switch was disabled, would seem hardly practical. As the load continues to grow with enormous strides, it would certainly seem that a more powerful type of switch should be found. As far as ascertained, resonance rises of potential due to the opening of an arc in an oil switch are of comparatively rare occurrence. It is natural to suppose that, whatever changes are made, the arc will still be broken under oil.

A few remarks of a general nature on switchboard construction and arrangement may not be out of place. A feeder switch, or circuit-breaker includes properly the knife switches separating the switch from the underground cable system, the series transformers, relays, control wiring and the switch itself with its fireproof compartment. It would not, therefore, seem illogical to adopt a type of construction in which all of these parts are relatively close together, instead of being scattered perhaps hundreds of feet apart as is frequently the case. For instance, the series transformer; the relays, the current through the coils of which, incidentally, should also pass through the circuit ammeters of the operating board, and the actuating mechanism of the switch belong together. The cable knife switch should be so placed as to be visible when working on the circuit breaking switch itself—in other words, in the base of the switch compartment. The bus bar knife switch should also be visible to any one working on the selector switches to obviate any chance of mistake in switching, and, furthermore, to protect the operator. This means, then, the bus bar and selector switch compartments must be one, so constructed that every switch section is independent and that the complete demolishing of one switch will not in any way affect either the neighboring switches or the bus bars themselves. This arrangement, mentioned above, will not only greatly reduce the space required for present switchboards, but will assist materially in proper maintenance and repair.

It is possible that it may become good practice where the plant equipment includes two switches in series for each feeder—one automatic and the other non-automatic—to allow the time element relay to open both switches in order to assist in breaking the arc, although this should not be necessary with a reliable switch. In connection with the use of choke coils the suggestion has been made that these coils be short-circuited by a heavy switch which would be opened by a relay when required. It is doubtful if any switch yet constructed would be quick enough to give the effect desired and on this account, and also on account of simplicity, choke coils, if installed at all, should be so designed as to care for operating conditions without the intervention of an iron core or moving mechanism.

As an illustration of the exceedingly heavy duty required even of a 300-ampere switch on a single feeder cable in the case of a 50,000-kw. steam turbine station of 6,000 volts, the instantaneous short-circuit current would amount to $50.000/\sqrt{3}\,E \times 50 = 240{,}600$ amperes per phase, or a kilowatt output, assuming a power factor for the short circuit of 40 per cent, of $50{,}000 \times 50 \times 0.40 = 1{,}000{,}000$ kw.

A 100,000-kw. plant under similar conditions would give an output of 2,000,000 kw. It is expecting a great deal of a 300-ampere switch to suppose that it could be safely figured on to care for such an enormous amount of energy. Yet the facts remain as stated. There are several modifying conditions, however, which enter into the problem. In the first place, short-circuits as a rule are not absolute short-circuits, and in this way the number of amperes actually interrupted is probably far less than that calculated. It must also be borne in mind that even if a circuit-breaker on a feeder were provided with an instantaneous relay, the time element of the switch itself is considerable, so that by the time the arc had been opened, the armature reaction of the machines would have, to a certain extent, become effective, thereby dropping the voltage and still further lowering the amperes at the break. If the safety of the switch alone is considered, it would doubtless be expedient to install inverse time element relays in connection with the feeders which would give an exceedingly long time interval in connection with the 100 per cent or more overload setting of the breaker, in order that they might give perhaps a three or four second interval between the occurrence of the short circuit and the opening of the switch. While specific information with regard to the length of time which is required for the armature reaction of alternators to become effective is lacking, there is no doubt that a mean might be drawn between conditions most favorable to the switch and those upon which depend the stability of operation of the main and substation synchronous machinery. Were it not for the possible rise in potential due to the breaking of the arc when the current is perhaps at a maximum instead of at zero point of the wave—which is another fact upon which further light is much needed and upon which the oscillograph without doubt will prove of great assistance in effecting a solution—the operating man would much prefer to have a short circuited cable cut off instantly before the trouble has had time to reach its heaviest proportions or has become severe enough to interfere with the frequency or voltage of the system.

The problem of the oil switch demands the more nearly exact solution of these questions. The protection which might possibly be afforded against the effect of static surges by the aluminum cell arrester might well be considered in this connection. With this protection, it would seem that the advantage lies practically altogether in favor of opening the switch itself as quickly as possible, by which it is understood that the greatest reasonable amount of time should be given by means of the relay to the switch before the latter starts to open the arc without, on the other hand, taking chances of throwing off the synchronous machinery. Under the best of conditions, however, we can but see that the switch is a relatively weak link in a system involving millions of invested capital.

The breaking of a circuit consists of inserting more or less gradually into the circuit a resistance which grows at a variable rate from zero to a maximum. At the moment the switch is leaving the contact, the greater the $C^2 R$ loss in heating, and especially if the circuit be inductive, the greater the amount of arcing. The rapid falling off in amperes as the resistance is increased by distance, when a considerable amount of metal is vaporized, and by this means the breaking of the arc is considerably hindered, is probably not at first accompanied by any great drop in the heating effect on the oil and the contacts, the $C^2 R$ loss for a certain length of time being perhaps practically constant. This, in part, is probably the cause of the explosive pressure set up in the cylinder by the oil vapor assisted by the actual displacement of oil by the arc itself. The prolonged arcing is evidently also the cause of the large amount of carbonization which takes place on opening a heavy short-circuit under oil with the modern switch.

Although there has not been a great deal written upon the exact nature of what takes place when a heavy arc is thus broken, experimental evidence has shown us that the quality of the switch oil will without doubt play a very important part in the switch of the future. The electrostatic stress set up between two charged conductors in a light mineral oil such as is used in switches and transformers, will, under proper conditions, even though no appreciable current is allowed to flow, release considerable quantities of gas without appreciable change in the oil itself, and as this gas is naturally rich in hydrogen, may it not be that the explosive violence of some of our short circuits is due to the combination of this gas and the gas driven off by the heat of the arc with oxygen, possibly of the air? The carbonization which takes place when a heavy short-circuit is broken is sometimes sufficient to make a deposit on settling of ⅜ of an inch in a 4-inch column of oil, or a total volumetric proportion of 10 per cent between the amorphous carbon and the clear oil above. The actual sample measured was taken from an oil switch cylinder from which two-thirds of the oil was blown out by the violence of the explosion. The physical analysis of the fresh oil (No. 6 transil oil) was as follows:

Flash	353 deg. fahr.
Burn	402 " "
Gravity at 60 deg. fahr	31.4 B.

As regard acidity, the oil was very nearly neutral, 0.09 per cent of potassium hydrate being required to neutralize same. There was no organic matter present. Various tests were made to ascertain the specific resistance and the dielectric strength of the above oil under the following conditions; first, the new oil; second, the blackened oil as taken from the switch; third, the clear oil after filtering off the carbonization. Careful tests were made under different conditions such as the sparking distance between needle points, between flat disks, between two ¾-in. balls, between a needle point and a disk, between a needle point and ball, etc. In some of the tests it seemed that the filtered oil after heavy carbonization showed an increase in specific resistance over the new oil. The dielectric strength also seemed materially increased after carbonization and filtering. The carbonized oil as taken from the switch showed a specific resistance of only one-fourth that of the new oil or of only one-eighth the resistance per cu. cm. of the oil after removing the carbonized particles by filtration, although another series of tests of other samples of the same oils failed to confirm the above figures; still there was a marked difference between the samples, although any increase in specific resistance or in dielectric strength failed to materialize except in one instance. The following figures, however, which are abstracted from the second series of tests represent the sparking distance between two ¾-in. balls at approximately 22.5 deg. cent. under a depth of oil of 2¼ in.

Sample	Gap	Volts
No. 1—Blackened oil (filtered)	0.15"	12,000
	0.20"	29,000
No. 2—New oil	0.15"	12,000
	0.20"	29,500

The following figures, representing the break-down point in inches at 30,000 volts pressure, as measured by an electrostatic voltmeter, checked by needle points, are also given:

Sample	Needle points	Needle and ½-in. disk	½-in. Ball and ½-in. disk	Between ½-in. balls
	in.	in.	in.	in.
No. 1—Blackened oil......	0.635	0.610	0.320	0.220
Blackened oil filtered........	0.530	0.750	0.250	0.190
No. 2—Blackened oil......	0.420	0.675	0.615	0.310
Blackened oil filtered........	0.300	0.600	0.290	0.185
No. 3—New oil...........	0.575	0.755	0.502	0.665

Temperatures in the above table all 26.5 degrees C.

All distances were measured by michrometer, the voltage adjustment being secured by finely adjusted resistances in the primary of a 40,000-volt testing transformer. As this may have introduced possible error due to change in wave form the figures are given as being perhaps at best, only approximately correct.*

Whether or not the changes in an oil produced by carbonization under heavy arcing improves or reduces the values of the remaining filtered oil for use in oil switches, it seems quite urgent that oil for switch purposes be chosen with great care, and manufacturers should make public satisfactory specifications to cover such oils and the testing of the same. It is by no means certain, as is frequently claimed, that a good transformer oil will make a good switch oil. Carbonization under heavy arcing is undeniably unavoidable. The study, however, of the physical and chemical nature of the actual conditions existing while the arc is being drawn through the oil with regard to the oil itself may lead to valuable conclusions that will somewhat strengthen the present oil switch situation.

It may be necessary to reduce the carbon content of the oil or possibly the hydrogen and more volatile components, even perhaps at the expense of changing the viscosity. Careful specifications will be welcomed by operating companies.

The severity of the arcing is naturally dependent upon the pressure of the oil surrounding the arc, the temperature of the oil and contacts, the velocity of switch opening, and, of course, by the ampere density at the point of break. The amount of vaporization of the contacts should be reduced to a minimum by properly proportioning the switch parts, by artificial circulation of the oil across the contacts as they are separated, and by increasing the velocity at the break to as high a degree as is possible. Severe arcing, even under oil, may without doubt be sufficient to set up heavy oscillations in a large underground system and, although much has been written upon the advisability of retarding the switch in its action, it frequently seems very advisable to have an absolute short-circuit broken as quickly as the switch will open it, the limiting factor being the reliability of the switch itself.

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* Other interesting figures in connection with the same kind of investigation are given in a paper read before the Manchester Local Section of the Institution of Electrical Engineers, by W. Pollard Digby, and D. B. Mellis, of which an abstract appears in the London Electrician, April 1, 1910. Important papers on this subject by Messrs. Skinner, Kintner, Steinmetz and others have appeared in the technical press.

The oscillograph in the near future will also doubtless add to our knowledge of the conditions existing in a severe arc closely confined, as in the case of an oil-switch cylinder under pressure. As stated above there seems to be considerable difference in opinion among engineers with regard to whether the opening of a switch should be in a horizontal or vertical direction. While many of the high-tension switches in the West use a horizontal break, depending upon a large volume of oil and a narrow knife blade for contacts, practically all of the high-power switches of moderate voltage have a vertical throw, in some cases opening by gravity, which has the advantage that the switch can never accidentally fall into contact; while in other types the switch opens upwards.

There has been developed, although apparently it has never yet been introduced as a commercial article, an oil-switch in which the oil is at all times under pressure which is maintained by a compressed air system—a pressure line of perhaps 150 or 200 lb. caring for a number of switches, and a gravity or return line returning the discharged oil to the system. This principle seems to be exceedingly promising insofar as breaking the arc is concerned, the switch cylinders being either always full of oil under pressure, the opening of the contacts allowing a heavy stream of oil to be forced directly across the arc and through the hollow contact to atmospheric pressure, or as in another case, where the tripping coil opens an oil valve which admits large quantities of fresh oil under pressure to come into direct contact with the heated terminal directly at the base of the arc. It is undeniable that the mechanical squeezing out of the arc is what we need.

The forcing of considerable streams of cooled fresh oil across the contact face to the atmosphere, thereby eliminating all carbonization and gasification from the oil switch itself, gives a pleasing prospect of what the future may have in store. The breaking of a heavy arc by the weight of a nine- or ten-inch column of oil, especially in small or confined areas is going to be somewhat of a doubtful matter especially as the sizes of operating systems increase.

Another matter which should be carefully considered in connection with the vertical cylinder oil switch is the magnetic repulsion between the oil switch cylinders at times of heavy short circuits. Insulator bases are required, of great mechanical strength, to safely withstand this unusual strain which is perhaps similar in its nature to that which causes the opening of high tension switches under similar conditions, and it may be perhaps that broken base insulators may be traced partly to this cause.

In the matter of oil-switch contacts, practically every form imaginable has been tried particularly in the smaller switches. It need only be mentioned, therefore, that there seems a strong tendency to rely upon the cooling effect of the oil and the large radiating surface of the pot or oil tank to carry off the heat from contacts which in air would run exceedingly warm. An oil switch contact should on account of the very nature of the insulating medium be of at least as large proportions as a similar current carrying contact for use in the air; especially so since carbonization, sedimentation, moisture and other causes may interfere with the contact; and, above all, because it is practically out of sight at all times.

Switches of the more powerful types are generally sufficiently provided as to contact area, but there are certain switches of high current carrying capacity designed for mounting on marble switchboards, for hand or solenoid operation in which the contact surface is naturally too small. The switch, including the oil and the oil tank itself, run exceedingly warm with the contacts most carefully adjusted. This seems a mistake and should never exist in any oil-switch which is placed in a position of responsibility. The temperature of such a switch contact cannot be noticed by handling as can that of a low tension knife switch, so that the greater amount of power per ampere precludes any cutting down of contact area if at the expense of a rise in temperature over normal conditions. Information as to the increase of conductivity of a contact due to increase of pressure is not very plentiful for contacts under oil.

The operating mechanism of large oil-switches can be of the pneumatic, hydraulic, solenoid or motor type. The pneumatic control seems especially adapted for switches of extra high voltage and of certain types, although these switches are very frequently solenoid operated. In the switches of systems of large ampere capacity, the choice between solenoid and motor types of mechanism seems an open one. Both types are fulfilling their proper functions in a satisfactory manner, so far as can be ascertained.

The method of control and the wiring of the same vary with conditions. Generally, the pilot switch that stands in the "off" position and inclining toward the contact last in use is adopted, principally for reasons of wiring connection. The style of pilot switch which remains in contact until thrown into another position is a most excellent switch, and for some reasons, especially in synchronizing, is preferable to the open type, if connections allow of its use. Certain switchboard designers prefer the pull-button switch where all the contacts are on the under side of the operating table, thus precluding any possible switch action due to the dropping of any conducting body upon the operating table, and thus operating switches at inopportune times.

Generally, the simplest switch seems the best, and with a switchboard comprised of plain knife switches so that the operator can always see that his contact conditions are satisfactory, the limit of simplicity has been approached. Synchronizing by pulling out a switch seems perhaps the least bit awkward as contrasted with throwing it in. Not only is it advisable as stated below that the circuit ammeters shall indicate any open circuit condition of the relay coils, but it is advisable if possible that the control wiring be so installed that the operator is informed by his pilot lamps in case of any failure or open-circuit condition in actuating current supply through the relay or the pilot switch itself.

Standardization in the case of oil switches has been made somewhat difficult, so that an excessive number of spare parts must at times be kept in stock. It seems unfortunate that several types of motors, for instance, all of the same general size, speed, and voltage shall be necessary, frequently perhaps on account of the changes of the distance between shaft center and base or a slight change in the base clamping arrangement. The same, of course, applies to motors on governors, main field rheostats, field-break switches, etc. In laying out a new station the designer should see that the number of types of auxiliary motors are reduced to a minimum, so that instead of six or eight or even more types, two or three will fulfill the conditions.

The interlocking of high power switches has not generally seemed advisable up to the present date excepting through the control wiring scheme. It is, of course, always advisable that this be so arranged that the synchronizing plug or switch shall carry the actuating current of the selector oil-switch so that it will be impossible for the operator to synchronize a machine with one operating bus and throw it on the other. Interlocking is furthermore undesirable in many instances as the buses are frequently doubled up for various operating reasons, this arrangement affording a very flexible means of caring for the every day happenings of the central station system. In a system in which each generator and feeder consists of a main circuit-breaker and two selector switches any set of selector switches may be utilized for tying together the buses, although the generator switches will generally be used.

Interlocking in the smaller types of switches designed for mounting directly on a switchboard panel or otherwise has not as a rule seemed advisable. The great tendency toward cheapness of production has actually interfered with proper design of some of the smaller switches to such an extent that it is suggested that all unnecessary complications should be avoided and the money invested placed in the switch itself, providing only a first class yet simple operating mechanism. The smaller type of switch may be hand—solenoid—or motor-operated. When used as a circuit-breaker it must be installed in systems within the limits of capacity as given by the manufacturers. Its use on systems of the heavier class is not advisable unless in substation installations when it may be safely used as a single throw device for a bus selector switch, provided that a heavy type of switch is used as a circuit breaker. This lighter switch finds a very abundant field on account of its relatively low cost, especially on voltages from 2,400 to 13,000. It is frequently used as a remote control switch, as a manhole or pole-type switch, and on the outgoing 2,400-volt wires from alternating-current transformer substations. There is lacking, up to the present time, any adequate time element device for this useful switch, so that unless special relays are used on the switchboard, circuit-breaker setting by means of the tripping coils generally means the opening of every switch in the series on short circuit, which is extremely objectionable. The usual practice, therefore, in this connection, is to solidly block everything possible and to remove all blocks only at the time of known danger or when switching. This at best is a dangerous practice and it is hoped that at a near date some satisfactory time element device will be furnished with all such switches for station use, as this will not only make possible selective setting of the various switches, but will possibly protect the switch itself.

In the alternating-current substations of a generating system of any considerable size the double throw form of polyphase switch in which both of the main bus bars, for instance, of the substation enter one switch, is generally inadvisable, especially in the switches of large ampere capacity and one self-contained oil tank such as is being furnished at the present day. It is preferable to install two first class oil switches, one for each bus in such a situation that repairs to switches and regular overhauling can be carried on safely and all chances of trouble between buses, and also the necessity of lowering an oil tank with very small clearances while the switch is alive, is practically entirely done away with. This double-throw type of oil-switch in which the dimensions are reduced to a minimum and the design is influenced to a large extent by commercial conditions, is especially dangerous if used as a circuit breaker. The operating mechanism, furthermore, of many of the switches of this type is very frequently of too light a nature to be consistent with the responsibility thrown upon the switch. Further defects which are brought about by the necessity for economy of space in the same type are weak insulators, and weak insulator support, also the difficulty of aligning the contacts and the contact yoke and of keeping them in proper alignment. Loose insulators, loose studs, and leaking tanks are of very frequent occurrence with some types of switches.

If light duty switches are installed in situations where they can be called upon to open short-circuits beyond their rated capacity in kilowatts, the oil is badly carbonized, the tanks are liable to become damaged, the contacts burned excessively, and the switch emptied of its oil if not actually short circuited. The oil tank for these light duty switches should be given an ample margin of security and purchasers of switches, particularly those which are to be used on systems of large size even though they are not to open exceedingly heavy arcs should specify tanks of heavy sheet metal properly riveted and absolutely oil tight. A great deal of trouble has been experienced through leaking of switch tanks in which, mainly for reasons of cost, the weight of the metal has been reduced until the tank itself is much inferior to that of several years ago. A one-eighth inch boiler plate tank, properly riveted is superior in every way to the light weight tanks now so well known. These latter remarks apply particularly to switches for use on switchboard panels. There are certain occasions when commercial conditions step in and a switch is desired at a minimum of cost, even at the expense of a certain degree of security. The operating switchboard of any main or substation, however, is not a location where security can in any way be dispensed with.

There is urgently needed a new type of oil-switch of the cheapest form, preferably of the single-pole type, which shall be automatic in case of predetermined overloads, and which shall be capable of being installed in place of present line boxes on overhead 2,400-volt distribution lines. There is a wide field for the introduction of just the right switch in this connection. At the present time, the market offers no satisfactory device. As these switches could be made in enormous numbers and as the design may be made so that the factor of safety excepting only the matter of insulation, is not exceedingly high, it would seem that it should be possible to manufacture at wholesale such a device that would in a measure compete, even in cost, with the present enclosed fuses and line or manhole cut-outs.

Experience has demonstrated that constant vigilance is necessary with regard to every part of a generating system if service conditions are to be maintained at the highest point of reliability. Especially so is this true of the oil-switch in large systems. Certain defects can be noticed by visual inspection; others require the operation of the switch one or more times, while the inspector closely watches the mechanism and tanks. Still others can only be found by actually taking the switch apart and reassembling it. The inspection necessary, therefore, covers the knife switches, the insulators and contacts, oil-switch mechanism, tanks, rods, base insulators and compartment. To best accomplish this, the work of switch inspection may be sub-divided as follows:

1. Daily inspection of mechanism, tightening up of possible loose nuts, etc., general cleaning of switch. This covers all that can be observed with a reasonable amount of attention while the

switch is in service, and is given every switch whether carrying current or "dead."

2. Weekly inspection, covering the operation of the switch from four to six times to observe clutch conditions, tripping coils or contacts, open-circuits in wiring, loose parts, bolts, nuts, etc. This test also insures the switch being securely bolted down to its compartment. All doors are taken off or swung open, and tanks, rods, yokes, etc., examined leaky oil tanks cleaned up and any dirty base insulators cleaned off. This latter inspection has frequently located broken base insulators, insulators loose in their iron mountings, loose bolts securing base insulators, loose yokes and wooden shafts, and on one occasion a yoke and set of rods which had actually become disengaged from its clamp on the vertical wooden rod and fallen into the closed position, thereby closing one phase of the switch absolutely without the operators' knowledge. Defective alignment of cylinders, particularly in the case of the older type of switches, and improper switch action are also thus located. This inspection also locates leaky oil tanks, defective cable connections and terminal insulation.

3. Once a year every switch is completely taken down, each part cleaned and oiled, contacts brightened, supplied with fresh oil, and any minor defects that may have crept in are remedied as far as possible.

These three inspections have been found to cover fairly well the operation of the oil-switch in service. The whole of the work outside of the inspection itself is cared for by one man, excepting that the annual overhauling makes it necessary to add one helper to the force. This is in a plant of some 90 high-power switches.

The yearly inspection has discovered at times defects of a very serious nature which would not have otherwise been located, excepting through the failure of the switch mechanism to operate in service, and also troubles with the switch cylinders, rods or contacts. It is desirable that this systematic inspection be recorded, a separate card being used for every switch on which the various defects are noted. The main purpose, however, as stated above, is that the switches may be in working condition at all times both as to mechanism and the switch itself. Failures to operate when called for, defective contacts, low or defective oil, loose parts within cylinders, defective rod tips, or broken insulators may, any one of them be the means at a most inconvenient time of causing trouble. Further records of switch condition besides the details given from the above cards are obtained by grouping the various defects in order that the weak points of the switch may constantly be kept in mind. The number of times the switch is thrown under inspection exceeds in all probability the times that it is actually used in service and has a tendency to cause a certain amount of switch trouble itself by loosening the bolts and contacts. It, however, is the only means available whereby the switch action may be entirely depended upon.

Type H Switch Record—1909

Minor adjustments not noted

	In service	Weekly test	Yearly overhaul	Total
Failed to open	0	0	0	0
Failed to close	6	10	0	16
Pumped	0	5	13	18
Oil renewals	7	0	81	88
Oil thrown on short-circuit	7	0	0	7
Contacts renewed	7	0	13	20
Base insulator loose or broken	0	19	9	28
Failure to open short-circuit	0	0	0	0
Defective contact at brushes	0	0	12	12
Broken castings, bearings, etc	0	0	5	5
Bent crank shafts	0	0	1	1
Clutch, trip coil and control finger troubles	0	35	2	37
Friction in mechanism	0	0	27	27
Troubles with compartments	0	0	2	2
Closed accidentally	0	0	0	0
Opened accidentally	0	0	0	0
Switches operated, times				35,000
Short-circuits opened	12	0	0	12

The daily inspection thus eliminates the minor troubles apparent to a trained observer; the weekly inspection makes it possible to practically eliminate all external troubles in the switch compartments and in the mechanism, and especially failures to operate when called upon, whether due to open tripping coils, defective clutch coils or otherwise, and practically insures the switch against trouble due to pumping; while the yearly inspection cleans up the switch as a whole, making it possible to start a new year with switches fresh and complete from top to bottom.

The actual expense for material in switch maintenance is probably equal to the labor item. The results obtained in a year's service, including operation and inspection of some 90 switches, subdivided into trouble of the mechanism and those of the switch proper are shown in the foregoing table.

In conclusion it may be briefly stated that the present state of oil-switch development, particularly described above, with especial regard to its continued use in the large installations of the future, has not given the operating man quite the same vision of perfect security and unlimited capacity as he would desire. A more powerful switch is seriously needed, a switch which will stand up in continuous service for at least a year without the necessity for overhauling every time a short-circuit is opened. It would not seem unreasonable to wish for this condition in any piece of machinery; and without doubt the oil-switch will be brought up to the standard desired when the operating companies and the manufacturers get sufficiently close together. The use of oil in the future switch seems assured. The problem is the right way to use it. From the standpoint of the present enormous and growing investments that are being protected by the device, and with a clear knowledge of the result of failure, there is no doubt that between the designer and the user and with perhaps the assistance of the physicist and chemist that the problem will be readily solved, when once its real importance is fully comprehended.

DISCUSSION ON "THE MODERN OIL SWITCH WITH SPECIAL REFERENCE TO SYSTEMS OF MODERATE VOLTAGE AND LARGE AMPERE CAPACITY". JEFFERSON, N. H., JUNE 28, 1910.

Peter Junkersfeld: Oil switches or circuit breaking devices seem to require some further development. There is need for something different, apparently, from that which we have at the present time. My own observation is confined, principally, to what Mr. Cheyney classes as the moderate voltage, high capacity switches. This class of switches seems to be very popular. A favorite question asked of the power station man is—"Do your oil switches always open the circuit, have they ever failed to open the circuit properly?" The usual answer, perhaps given with a little hesitation, is "No, they have never failed to open the circuit." I myself have answered that question a good many times, and have been frequently tempted to add—"Yes, they have always opened the circuit, but at what cost and with what results?" The system I have in mind has at present three hundred oil switches in three different generating stations, and if the substations were included, the total would be over five hundred. The number of times that the switches were distressed was few—very few in comparison to the total number of switches. The percentage of the times when all of the oil, or a large part of the oil, was thrown out of the oil vessel, to the total number of entirely satisfactory switch openings, is also a small percentage, but it is still too large, for the reason that the amount of property involved and the number of people inconvenienced is such that the reliability, so to speak, should be increased.

There is a very urgent demand for this increase in reliability. Moreover, from the standpoint of first cost, it would seem we are perhaps getting a little bit out of balance. The very fact that occasionally a switch is perhaps, entirely wrecked, means that there is a demand and a necessity for very expensive bus-bar structures, and everything of that sort, to prevent the trouble from spreading, and this has reached a point where in many systems the cost of the various oil switches, switchboard equipments and bus-bar structures, etc., is practically equal to the generating end of a steam turbine unit.

That, as I said, from an economic viewpoint, looks as if we are going too far, but we are driven to it in order to provide the degree of reliability of service demanded. It would seem also, that in this matter of interrupting circuits, there is really no mechanical analogy, that I can think of, for the moment at least, for attempting to stop the enormous momentum in electrical circuits. Mechanically, if we stop a moving mass, we apply the brakes gradually, but with an electric circuit we attempt to stop it almost instantaneously. It would seem we should insert something in the circuit, such as has been suggested, and on which work has been done in the last year, in the way of reactance. That would seem to offer a solution insofar as it would reduce the burden now placed on the oil switch. However, the progress in that direction has not been as great as we could wish, because there are many difficulties in designing and building of reactances to stand these large powers. Moreover, the experience with oil switches for very large capacities seems to have been almost entirely with one general construction, and in the present state of the art, only one thing seems to be possible for use with very large units and that is to require a somewhat larger oil switch.

Ford W. Harris: This paper is one much to be commended both on account of its being a logical array of facts from a man who knows, and on account of its general tone of fairness and moderation. Mr. Cheyney believes the oil switch is the weak link in his chain of apparatus and it is very hard to speak fairly of the weak link.

This subject of oil switches is daily assuming a greater importance due to the constantly increasing capacities of our large stations. For some years the design of oil switches has remained stationary and what was five years ago a thoroughly dependable device is now being looked upon with suspicion.

There is no question that there is not at this time on the market any oil switch which can be depended on to open heavy short circuits on powers above 10,000 kw. at 11,000 volts or below without certain manifestations of distress.

These manifestations of distress may be grouped into three classes:

1. The throwing of oil from the tanks.
2. Excessive burning of contacts.
3. Distortion of rupture of tanks due to heavy pressures generated in them.

These troubles are in themselves serious but there are two facts that in a great measure should reassure the operating engineers of the country in regard to the present status of the oil switch; these are:

1. That in no case of which we have record has an oil switch failed to clear the circuit, providing it was in normal condition upon the occurrence of short.
2. That it is only on powers above 10,000 kw., and only then if this power is concentrated at the switch, that any trouble whatever occurs.

Mr. Cheyney seems to feel that the present unlimited breaking capacity guarantee on the heavier switches is unreasonable. For some years after these switches were put in service these guarantees were absolutely correct as no complaints developed. As, however, power houses grew larger and turbine-driven generators became common the three troubles previously given developed. The manufacturing companies found themselves confronted with a growing difficulty for which they knew no remedy. Operators in general seemed to feel that the function of the switch was to open the circuit and that this was what was guaranteed. The throwing of oil and kindred troubles are, in themselves, not incompatible with such guarantees and at the present time are an understood accompaniment of oil switch action on heavy short circuits.

This latitude of the manufacturers was not based on inertia but on the difficulty of the design problem presented. The study of short circuits is a study of calamities. The testimony of people who have seen short circuits is of little value. Practically the only remedies were in the laboratory and the study of actual short circuits produced wilfully on heavy power stations with their attendant life and property hazards. Since these large power stations are rare and since no operator will wilfully short-circuit his bus bars, except under considerable pressure, progress must of necessity be slow.

The laboratory study was undertaken and proved very illuminating, and within six months three large power stations have permitted wilful short circuits of great magnitude. The result has been a considerable mass of data which will be later incorporated into a fairly complete exposition of oil switch theory. Better yet, these tests and certain practical service tests indicate the line further development should take. It now seems perfectly possible to develop devices which will repeatedly open without injury to themselves or the circuit any current which may be generated. It is thus seen that the manufacturers are not resting idly on their present designs but are pushing forward with good prospects of success. We hope within a few months to present to the Institute a complete record of such success.

There is, however, another side of Mr. Cheyney's paper. There are, of course, varying degrees of excellence in the oil switches now on the market. The present designs are pretty much standardized along certain fundamental lines.

These fundamentals of design are pretty generally observed by all oil switch manufacturers in this country and abroad. The designers of the switch on which Mr. Cheyney's paper was based evidently aimed to produce a switch of great rupturing capacity and have adopted a design that necessarily violates some of these fundamentals. Some of Mr. Cheyney's trouble seems to be due to this. It seems to me that a statement of these fundamentals and a discussion of their bearing on the problem may not be out of place. I would, therefore, submit that in any high-tension oil switch the following main principles should be incorporated.

1. There should be no exposed live metal parts. Switches in which oil pots are alive even if they are enclosed in a cell with a door form a very dangerous life hazard and a source from which dangerous arcs start.

2. Switches should be so arranged that gravity will tend to

open the switch so that if mechanism is in the open position the switch will be open. The falling closed or staying closed of a switch which should be open is fundamentally wrong. The breakage of mechanism at any one of several points on such a switch would result in life and property hazards that cannot be ignored.

3. An oil switch should have all breaks under oil. In the heavier capacity switches of the type in question an auxiliary main brush is used to finally close the circuit in parallel with oil break. The destruction of contacts in oil will throw the whole duty on the air break with a probable total destruction of switch and a bad oil fire.

4. Mechanisms to be permanent and reliable should be self-contained. The fastening of one part of mechanism on top of brick cell and supporting the remainder on porcelain insulators and expecting permanent alignment under the enormous stresses of short circuits is bad practice which should be avoided. Each pole should be operative outside of the structure and permanently aligned to some substantial frame at the factory of its maker.

5. Solenoid operation rather than motor operation. As one who has designed good, bad and indifferent switches, both motor and solenoid operated, I cannot too strongly urge the claims of the simpler cheaper and permanent solenoid as against the motor. What is needed in any switch is a sure short and powerful stroke and to obtain this by gearing down a small torque at high speed into a compressed spring must result in a complicated mechanism. These mechanisms and the motor itself require frequent inspection and adjustment. The trouble mentioned by Mr. Cheyney as "pumping" is a very serious one. As I understand it, this means that in opening or closing, the switch fails to stop at the appointed place but throws in or out violently several times. The effect on a circuit of such an action cannot be good, and the effect of throwing a short circuit alternately off and on generators must be very bad. Such action on a solenoid operated switch is obviously impossible. The 18 cases mentioned by Mr. Cheyney of such "pumping" were luckily all caught by his inspection.

In general it may be said that Mr. Cheyney's inspection as detailed by him is very thorough and is an exceptional condition. It is reasonably certain that such inspection cannot be expected except in a very efficiently managed station and that the table of troubles made up by Mr. Cheyney represent the very best of operating conditions. In thus outlining his inspection he has indicated what one operator is willing to do to keep apparatus in first-class condition and while such exceptional care cannot regularly be expected, an improvement in this particular can profitably be made in many stations.

C. W. Stone: On the first page of Mr. Cheyney's paper he says "that it is probable that we could get the manufacturers to construct switches to open safely short circuits under the worst possible conditions in systems of unlimited kilowatt capacities, the only limiting condition, of course, being that the consumer be willing to pay for it." I rather doubt this possibility. I do not believe we can get switches that will open under the worst possible conditions, that is, instantaneously. If Mr. Cheyney means a type of switch which opens slowly after the disturbance is largely over, then I would agree that it is possible.

Mr. Cheyney says that a large volume of oil greatly increases the factor of safety. My experience has been the other way—a large body of oil does not increase the factor of safety, unless we assume the same type of switches in both cases. Take a switch mechanism similar to the type H switch; if these oil pots contained a larger body of oil, there is no doubt but the effectiveness of the switches is increased, but if we compare this type of switch with any other standard plunger type of switch, and use a larger body of oil, the H switch will open many times the capacity. Even in the larger high voltage switches, such as the 110,000-volt switches, a large single plunger type switch will in all probability open a heavier short circuit than a large square, or oval, or round tank similar to the other types of switches in use on the Pacific coast.

Another objection to the large amount of oil is if there are one hundred and fifty switches in a station, it is not desirable to have so much oil in a station on account of increased fire risk.

Mr. Cheyney mentions the enormous growth in the transmission systems, and therefore the necessity for larger switches. Why, if we limit the capacity of our system, or the sections of our system, and install reactance, such as has been proposed in a number of cases, and such as is being done, or at least being projected, is it necessary to have larger switches? I think the reactance will tend to limit possible damage in case of short circuits, and possible disturbances of the system; that is, disturbances will not grow to such an extent if the reactances are used. Mr. Cheyney mentions that later on, and I agree with him fully.

I think the object of the oil switch is to clear the circuit from trouble. We can keep the trouble on a little longer, and thereby save the switch. Is it not preferable to destroy the switch, if we can clear the circuit, and according to all the experience I have had the switch always opens the circuit. Suppose we cut off the damage from the switch, will not that damage something else on the system which will cost more to replace?

Mr. Cheyney says "Choke coils to limit the generating capacity in one section of the bus to a value of perhaps 20,000 kw., or a capacity slightly above that quoted when the switch was disabled, would seem hardly practical." There is no doubt but that this is a very difficult problem to solve, but I do not think there is any reason to suppose that in a few months that problem will not be solved satisfactorily.

Mr. Cheyney also says that the knife switch in series should be placed in a compartment below the oil switch. I know this is the practice in a number of cases, but I do not agree with it. I think it is the worst place you could choose. The object of the knife switch is to cut the oil switch out of circuit, when the oil switch is to be inspected. If you have immediately below the oil switch some live terminals, why are you not increasing the risk of the operator when he tries to make an inspection of the oil switch, as he must necessarily work within three or four inches of the live circuit? I think that is undesirable. I have also felt that the knife switch below the oil switch is dangerous. unless locked in position, because in bad short circuits the knife switch has been thrown open, before the oil switch could act, due to the violence of the short circuit.

Mr. Cheyney mentions the effect on the system due to heavy short circuits, that is, interfering with the frequency or the voltage of the system. I think if we use reactances we would limit that effect and provide for such disturbances.

I note that Mr. Harris objects to exposed metal. I think it is a very good plan to cover up all the metal you can, but if you do it at the sacrifice of something else I think you had better expose the metal. My experience is the safest switch is the switch in which the metal is exposed and surrounded by a brick compartment. Then any trouble which may occur will be confined to that brick compartment. The mere fact of putting insulation around the oil pot simply tends to increase the fire hazard.

My experience is not exactly the same as Mr. Harris' in regard to the "pumping" of oil switches. I have seen a good deal of trouble in several cases, due to severe pumping, with solenoid-operated switches. I have seen these switches pump just as much as the motor operated switches. My experience is that the solenoid operated mechanism is more costly and complicated, and less liable to operate in case of low voltage on the operating circuit than the motor-operated mechanism. A motor-operated mechanism can be designed so that the opening of the circuit is independent of the motor, whether the motor moves or not. I think this type of switch will usually clear the trouble better than any type of solenoid switch I have ever seen.

D. B. Rushmore: The functions to be performed by oil switches vary greatly, and the resultant troubles in their operation depend to a large extent upon the particular service for which they are used. Small hand-operated switches are often opened and closed but a few times during the twenty-four hours. Large high-tension switches are as a rule very seldom operated. Other switches which may be used for intermittent motor service in connection with control apparatus may operate at intervals of a few seconds. We thus have a wide field of application and no one switch can be expected to be equally satisfactory under all the various conditions of operation.

During the last few years there has been a very rapid increase in the generating capacity tied together in the large Edison systems, and these present one of the most difficult problems of switching.

As a criterion regarding the satisfaction which a piece of electrical apparatus may have been giving, nothing is better than a study of the facts in connection with its use. It is a matter of record that certain types of oil switches in use have had complaints concerning their operation which amounted to a fraction of one per cent, and a piece of apparatus with such a record can be called highly satisfactory.

Mr. Cheyney's paper should not in any way be taken as an attack on oil switches. Very seldom is a record made of good, successful performance. It is only in the failures and disturbances that we are particularly interested, for it is desirable that our attention be concentrated upon these. Generators fail, transformers blow up, and every piece of electrical apparatus is liable to disturbance of some kind.

Of late a great deal of experimenting has been done with oil switches, the results of which are embodied in apparatus rather than in a history of experimental work. The horizontal switch of which Mr. Cheyney speaks is used to a certain extent in California. Before being manufactured there, it was brought out in the East by one of the smaller electrical companies. It has, however, certain limitations, and under some conditions affects unfavorably the limitations of power house design. Up to the present its use has not become very general.

Certain types of switches before they have been put on the market have been subjected to endurance tests in opening hundreds of short-circuits in rapid succession.

High-voltage switches are in an altogether different class. The difficult problem before operating and manufacturing companies is the one of developing switches for use on circuits where very large capacity of generating apparatus is installed, and especially where automatic relays are used with the switches.

In high-tension switches the difficulty is largely one of insulation. For use with the highest voltages, it is not an easy one to solve, and in switches recently developed where the specifications called for a high-potential test of 300,000 volts a considerable amount of experimental work was necessitated in connection with the development of such apparatus, the results of which have, however, been entirely satisfactory.

On the market to-day may be found a considerable number of what might be called "home-made" high tension switches, and these are to some extent used on the transmission systems on the Pacific Coast. At least one large power house has been destroyed as the result of the use of these switches. With them automatic attachments are but seldom employed, and they may be more properly considered as disconnecting oil switches, rather than as performing the functions for which a switch is usually installed.

On many systems the capacity of generating apparatus has increased far beyond what it was when some of the switches were installed. The throwing of oil in the switch is a safety feature, and is not an indication of the failure of the switch. Almost never is it reported that the switch fails to open the circuit.

New types of switch will be developed in the future, and with harmonious working between the operating and manufacturing companies, the new problems which constantly present themselves with the growth of systems and the development of the art will be given the same careful study which they have received in the past and will meet with the same satisfactory solutions.

C. P. Steinmetz: Before criticising the oil switch, let us see what it has done. Most engineers will agree that the operation of our present very large power stations has become possible only by the development of the oil switch. At the same time most manufacturing as well as operating engineers, will concede that still further improvements may be possible in the oil switch. Let us see what the problem is which we have to meet.

I do not agree with Mr. Harris' statement of the fundamental principles of the oil switch. It rather appeared to me that the requirements propounded in his discussion are not fundamental principles, but constructive details, mostly of a mechanical nature.

To still further improve the operation of the oil switch there are two ways; first, reduce the power which the oil switch has to control; second, improve the oil switch. The former is the problem of which the engineers have heard a great deal in the last year or two, because it is a problem which has to be worked out by the operating engineers, and manufacturers together—it means cutting the system into sections, by putting in reactance, so as to limit the maximum power which can be developed at any place. That is one of the first things which has to be done, because no oil switch can ever be designed, nor any other apparatus, to control unlimited power.

The second problem is to improve the oil switch. Though we do not hear so much about it, it is being recognized and worked out as industriously, if not more so, than the other problem.

In the paper we read about the desirability of using air pressure. This matter has been studied very thoroughly, pressure gauges have been put on the switch at various points to measure the pressure produced by the operation of the switch, by the energy of the arc which produces a rapid evolution of gas, and so brings to bear upon the break the pressure caused by the momentum of the oil, pressures which are far greater than any possible air pressure. After all, what the oil switch does, is to break the arc under the enormous pressure created by the momentum of the oil, which is to be pushed out of the way of the arc, and that pressure exerted is far greater than any pressure which you could maintain over the oil.

The action of artificially produced pressure has also been studied. I recall some very interesting experiments which were made by operating an oil switch under pressure. We had a pressure gauge on, the needle of which went off the scale at 2,000 pounds, and immediately afterwards the top of the oil switch, together with the oil—it was a heavy steel tank of bomb construction—went up into the air.

The oscillograph is a valuable assistant in the study of the oil switch, and many thousands of oscillograms have been taken in studying the performance of the oil switch, and in studying the performance of the circuits controlled by it, and we know a great deal about it, very much more than usually supposed, though we do not know as much as we would like to know.

You will realize the importance of the problem before you when you think what the oil switch has to do. Consider a system like that of the Commonwealth Edison Company, in Chicago, with a short circuit at the bus bars. The instantaneous power generated is between 6,000,000 and 8,000,000 kw. Now stand at the foot of the Horse-shoe Falls at Niagara and think of the problem involved in instantly stopping its power, and there you have the problem of the oil switch on a high power system. It is not an easy problem, and it is difficult to realize what we have to deal with. It is not the few hundred thousand kw. of the generators with which we have to deal, but the many times larger momentary power.

Now, what is the destructive effect on the oil switch? It is energy, but energy is power times time, and this means you can reduce the destructive energy by shortening the time. On the other hand stands the well established fact that the opening of the enormous power in too rapid time, destroys the system back of the oil switch. If you open the circuit too rapidly, the oil switch may be saved, but you destroy the cables and everything else. If you open it too slowly, you blow the oil switch to pieces by the energy produced there. Between these extremes you have to compromise.

The oscillograph records give us information how far we can reduce the energy of the oil switch by increasing the rapidity of the opening, without endangering the system, and that is work on which we are engaged. The fundamental principle of oil switch design thus is to open the switch with the minimum energy production in it, but at a rate slow enough not to produce destructive effects in the system controlled by the oil switch.

I have spoken of the oscillograph, and incidentally I may correct a misconception. It has frequently been believed that the oil switch opens the circuit at the moment of minimum stored energy, that is at the moment when the potential energy stored as magnetic and as electrostatic energy is a minimum. However, the oscillograph records, as far as I have been able to study them, point to the fact that, irrespective of the stored energy in the system, the oil switch opens at the zero value of current. For instance, in the charging current of a 100,000-volt transmission line, of say 150 to 180 miles, we have an electrostatic energy much larger than the electromagnetic energy, still the oil switch breaks at zero current, which is practically coincident with maximum voltage; that is, with maximum stored energy.

That is fortunate, because the cause of destructive effects is not the electrostatic energy of the system, but the electromagnetic energy. The electrostatic energy is limited by the voltage. We know, no matter what oscillation is produced by the electrostatic energy, the voltage can never more than double. It is less than double voltage, and since the double voltage is momentary, any insulation which can continuously stand normal voltage can momentarily stand double voltage. But in the rupture of the current the magnetic energy is unlimited; it can be anything up to the magnetic energy of the short circuit current, which is many times greater, especially in these high power systems, than any static energy, but that energy, fortunately, is not destructive in the oil switch, because the oil switch opens at the zero of current and thus zero of magnetic energy. It is very interesting to observe this on high voltage systems.

As I stated, there is sufficient evidence available to-day in oscillograph records, and it is being worked out at the present time, but that work is necessarily slow.

W. I. Donshea: Mr. Cheyney refers to a number of instances of the oil switch, of the type he has under consideration, successfully doing the work for which it was designed, and he mentions specifically one switch which opened 25 consecutive short circuits within a space of one-half hour, and also two similar switches which in three years opened several hundred short circuits without a change of oil. But he says, "The enormous growth of connected load and, at the same time, the adoption of the steam turbine as a prime mover, have brought about conditions unforseen; and not only has the ability of modern switch construction to safely care for the new conditions been questioned, but experimental evidence would lead to the conclusion that either a new form of switch is urgently needed, or else a marked change in switchboard construction and station operation."

The speaker is of the opinion that this view is not warranted, and he would cite the experience of a company which has in use about six-hundred and fifty of these switches, of which four hundred are located in the two power houses and the remaining two hundred and fifty in the twenty-six annex stations. The rated generating capacity of the two power houses is 160,000 kw., (all connected to one bus) of which 121,000 kw. are in steam turbine prime movers, that is of the type which the author mentions as imposing exceptionally severe duty on the switching apparatus. These switches are giving satisfactory service, and they have not failed in a single instance to disconnect the most severe short circuit to which the system has been subjected. This experience indicates that the present conditions were foreseen and that both the manufacturers and the operating companies were keenly appreciative of the importance of the interests they controlled, and had already designed on the one side and accepted on the other, apparatus which is capable of preserving both safety of equipment and continuity of service.

The author also refers to the need of overhauling the switches, examining contacts and replacing the oil and says, "This whole operation involves a period of at least two hours, and if spare feeders are not available may lead to considerable annoyance, while in any case it may involve a temporary disablement of a large and important investment in apparatus." But it is not customary to install a system of the magnitude suggested by the author without an ample surplus of capacity in feeders as well as in the other parts of the equipment. It is universal practice with such large companies to keep in service a sufficient number of generators, each with so high an overload capacity that any one of them may be disconnected without materially affecting the system voltage; a sufficient number of feeders (laid through duplicate routes) to the distributing stations, and connected there to machines, which, like the generators in the power houses, are in number and overload capacity ample to maintain the voltage of the system. On this point I might quote from Mr. W. F. Wells in a discussion of a similar subject in May, 1905: "In general sufficient equipment is installed and operated to render it possible at all times to disconnect instantly any individual or group unit, without interfering with the service. As the number of units increases, the proportion of investment in emergency or spare equipment diminishes and soon becomes of relatively minor importance. The interest and depreciation charges on account of this spare equipment are partly offset by the greater flexibility in operating and the decreased transmission losses." But unquestionably there is no large company such as contemplated by the author which would not recognize the principles of insurance as applied to reserve equipment as well as to fire and other hazards.

The author treats interestingly the subject of oil which has been exposed to severe arcing, but the results of tests which he reports are so variable that they seem to commend the practice of discarding all oil which has once been subjected to the strain of dissipating a severe arc.

In the concluding paragraphs the author says, "Constant vigilance is necessary." It is perfectly true that frequent inspection of all apparatus is both prudent and profitable. In the two power houses mentioned an inspector makes a tour through the switch rooms once an hour for the purpose of examining all parts which are exposed to view, and of locating excessive heat in any switch enclosure. In addition to this, all switches are cleaned once a week, and they are dismantled and reassembled once a year. Whenever a switch opens under load the oil is removed, (and this oil is either thrown away or used for other purposes) the contacts are overhauled, the entire switch thoroughly examined and new oil is put in. In short, every effort is made to maintain the entire switch equipment in a condition which is at all times as good as new.

What I have said about the existing switch must not be taken as indicating that I feel it is perfect or that there is nothing better to come, but it is a good switch; it is not a one man's idea, but as a previous speaker indicated it is a resultant of the policy of coöperation and consultation which has always existed between all the manufacturing and the operating companies. To use a homely expression, " both sides have been onto the job."

V. Karapetoff: It was interesting to note in this discussion that a more rational method for opening circuits behind a large amount of power is being discussed, and several speakers have mentioned the use of reactance coils. I should like to know more in detail the actual connections when reactance coils are used, that is to say whether such coils are connected between separate feeders, so as to limit the interchange of energy, or if they are permanently in series with each individual feeder; also, if such reactance coils must contain no iron? I should like also to inquire if the scheme has been tried of having series reactance coils normally short-circuited by the oil switch and automatically introduced into the system by the opening of the switch?

G. F. Sever: I ask Mr. Cheyney why he uses the value of 50 in determining the amperes per phase? That is not quite clear to me.

A. R. Cheyney: This paper seems to have been productive of a very valuable discussion. First of all I want to disclaim all intention of seriously criticising any particular switch, merely desiring in my paper to show the actual results which we have experienced with oil switches in actual service, and hoping that in the discussion new points with regard to design and operation might be uncovered.

In answer to Prof. Sever's question, I would state that the figure 50 used in calculation of short circuit current of alternators is a figure frequently given by which we may multiply the normal full load current in amperes in order to obtain the instantaneous value of the short circuit current.

In reply to Mr. Harris, I would state that in connection with the table of inspection from which he quotes, the examples of pumping did not occur in any instance with a switch in service. There was, therefore, no pumping of machine or feeder switches on short circuit with machines out of step.

I fully agree with Mr. Stone with regard to large and small volumes of oil in a switch, as he states a rupturing capacity of a switch with a larger cylinder and a larger amount of oil present is considerably greater than that of a switch with a small cylinder. The best means of obtaining a maximum rupturing capacity in a switch was one of the main points which I intended to cover in the paper.

The knife switches used in connection with the oil switch should of course, be separated from the switch connection proper by a fire-proof barrier, the point in this connection I wished to bring out being that it is quite important that the man working on switches should be able to see for himself the switch which absolutely protects him from possible injury. He can then rest assured that by no chance can the knife switch be closed without his knowledge.

Uncertainties with regard to the real necessity for reactances are being rapidly cleared up so that while a year ago we talked of reactances being necessary between two stations of 100,000 kw. capacity each, and possibly in connection with sub-dividing the bus-bar of a 100,000-kw. plant, now we are considering the proposition of reactances being absolutely necessary if we wish to protect the switch itself between sections of a generating station each of 20,000 kw. or under.

Professor Karapetoff has asked what wiring connections are used in installing the reactances. These are installed in several ways in accordance with the conditions confronting the designer of the plant. In the bus bar they would, of course, be directly in series with each bus conductor between sections. When installed on generating units they are sometimes connected directly in series with each conductor at the generator terminals and possibly also in connection with the grounded neutral. The chance of resonance troubles due to this series connection, particularly in large underground systems, has not yet been very fully discussed before the Institute to the best of my knowledge.

We are thus face to face with the following solutions:—First, install at very frequent intervals heavy reactances which will in all cases divide the station into sections of 20,000 kw. each as a maximum. Second, use the present switches without reactance and take the chance of serious damage to same and possibly a simultaneous interruption of service from the dropping out of step of a considerable part of the synchronous machinery. Third, the development of a more powerful switch. The latter solution seems to me so very desirable that I should hesitate to give up at this time all hope of its possible accomplishment.

E. M. Hewlett (by letter) In reviewing Mr. Cheyney's paper, the writer is much impressed with the excellent performance of the oil switches. It is gratifying to note that in all cases in service the switch opened the circuit on overloads and short-circuits and that the tests were thorough enough to develop practically all the faults during the test period. Considering that there were nearly 100 switches involved, it would seem that the oil was changed on an average of a little less than once a year per switch and less than two adjustments were required per switch per year.

Regarding simplicity of design, this point cannot be too strongly emphasized. It must, however, be remembered that the operating conditions imposed on the oil switches contribute in a large measure to the design. The switches are called for to be remote control, capable of being operated at some distance from the switchboard, automatic, sometimes with time limit and indicating devices to indicate the position of the switch, and many other extra functions. It should be appreciated that

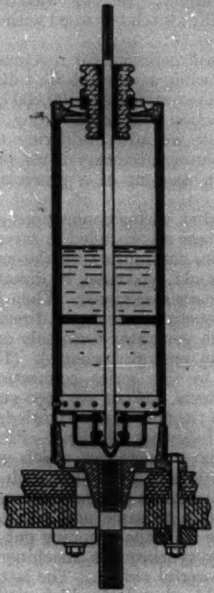

FIG. 1

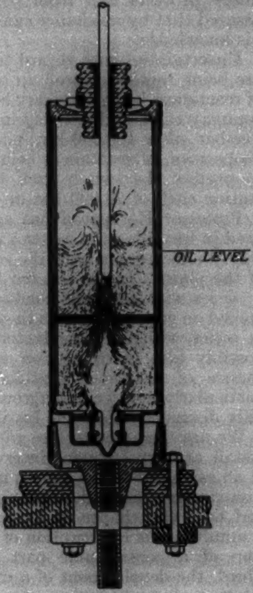

FIG. 2

these extra conditions and requirements have been demanded when considering the complexity of the switching device.

In order to discuss the oil switch situation it seems best to separate the subject into the mechanical and the electrical operation. The mechanical operation may be remote control by the means of compressed air, solenoids, motors, rods and bell cranks, according to the requirements of the case, using the best method fitted for the conditions.

The H form of switch with its motor driven mechanisms is designed for remote control operation, so that a large number of generator and feeder circuits can be gathered together where they can be conveniently observed and controlled by an attendant.

The three-phase H oil switch in its present form consists of six steel oil vessels, eight inches in diameter, with casting at the top supporting porcelain bushings through which the contact rods may operate. These rods, or arcing tips, make contact with a special four-segment contact under spring tension located in the bottom of the oil vessel, and are submerged in transil oil which has a high voltage breakdown point and will not easily carbonize. The depth of oil over the contacts in each vessel is eight to 10 inches, approximating two to three gallons per vessel. At the bottom of the oil vessel is a heavy clamp which serves as a mechanical support and at the same time provides an electrical circuit. For capacities over 300 amperes brushes are attached to the crosshead, which carry the main load current but do not break any load. Two oil vessels with contacts are used in each cell, thereby giving a double break for each of the three phases.

The high rupturing capacity of the H form of switch is due to the baffle plate or pressure chamber construction; Fig. (1) *i.e.*, the arc is sprung in the pressure chamber at the lower part of the switch and the gas generated by the arc expands and forces the oil under pressure through the same aperture that the arc is drawn through as it follows the contact rod (Fig. 2). This stream of oil under pressure driven into and across the path of the arc makes a very effective means of opening electrical circuits of large capacity with a small quantity of oil, the oil receptacle and baffle plates being made to withstand the pressures.

Owing to the flexibility of this construction it is permissible where large amounts of power are to be controlled to further isolate by means of separate compartments for each oil vessel with its individual break. As an extra insurance it is possible to install the mechanism above this layout, thereby affording protection to the attendant when adjusting neighboring switches, at the same time preventing the possible spreading of high power arcs to the low potential or control circuits.

From tests and experience it does not seem advisable to go to the extreme of placing the main contacts under oil, as it introduces serious complications.

The K form of switch, in which two or more arcs are sprung in one oil vessel, is used in switching moderate amounts of power and can be designed for ordinary cases until the pressure developed and the amount of oil required make it necessary to consider other design. This K form of switch is top connected and permits a very flexible bus bar layout. A switch of this nature is limited in its rupturing capacity due to its rectangular or oval tank, and the difficulty of confining the pressure and directing the oil in such a receptacle.

Regarding Mr. Cheney's statement on oil switch improvement, a high rupturing capacity H switch has been designed for stations with 20,000 kw. turbo-generator units.

Regarding the possibilities of switching apparatus, oil switches can be made to handle any generator or capacity desired; it being a question of space limitations, expenses and a knowledge of the circuit characteristics.

With very large generating capacities a switch designed to open the circuit instantaneously might be so large in dimensions that it would be prohibitive as a station device and the better plan seems, in order to keep oil switches of reasonable dimensions and moderate expense, to limit the conditions by sectionalized busses, reactances, time limiting devices, etc.

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DISRUPTIVE STRENGTH WITH TRANSIENT VOLTAGES

BY JOSEPH L. R. HAYDEN AND CHARLES P. STEINMETZ

I. General

Experience with high voltage transmissions and distributions shows that high frequency oscillations and other disturbances of limited power do not exert as high a disruptive effect, at least on oil and solid insulation, as should be expected from their voltage. Discharges have been observed between the terminals of high-potential oil transformers through the air, which require voltages far beyond those which the transformer insulation could stand, and the absence of a break-down of the transformer could not always be explained by the screening effect of the reactance of the transformer leads.

In his early investigations on high-frequency currents, nearly a generation ago, Professor Elihu Thomson observed that, relative to air, oil has a much greater disruptive strength for high-frequency oscillations than for steadily applied alternating voltages. More recently Professor E. E. F. Creighton has, as the result of his investigations, expressed the opinion that there is an appreciable, though very small, time lag even with air; that is, disruptive discharge does not occur instantly with the application of the voltage, but some time elapses before disruption occurs. This time depends on the nature of the insulating material, and also on the shape of the discharge path. This phenomenon is of industrial importance in the protection of electric circuits against over voltages of short duration, in two ways:

A spark gap of small time-lag may protect the insulation of apparatus against momentary voltages, even if set for a discharge voltage higher than the voltage which the apparatus could stand when continuously applied, if the time-lag of disruptive strength of the insulation of the apparatus is much greater than that of the protecting spark gap.

On the other hand, if the time-lag of disruptive strength of the insulation of the apparatus is shorter than that of the protecting spark gap, the latter would not give effective protection against momentary voltages, even if at steadily applied voltage it discharges much below the disruptive strength of the apparatus.

An investigation of the disruptive effects produced by transient voltages was therefore undertaken. Some of the results found with air and with dry white paraffine oil, are given in this paper.

For producing single high-voltage impulses of very short duration, the method used by Professor Creighton in his study of lightning phenomena was applied: a continuous voltage is impressed upon the primary coil of a high-voltage transformer, through a non-inductive resistance. During the rise of the continuous current in the transformer primary, a voltage impulse is induced in the (high-potential) secondary of the transformer. The height of the voltage impulse and its duration are determined by the continuous voltage of the supply circuit, and by its resistance. The total energy input to the transformer is determined by its inductance L and the final value of the continuous input i_0, as the energy of the magnetic field of the transformer, $\frac{i_0^2 L}{2}$.

II. METHOD OF TESTS

To study small amounts of energy at high voltages, a small transformer had to be used, and considerable difficulty was first found in avoiding oscillations due to the internal capacity of the transformer winding. The arrangement of circuits shown in Fig. 1 was found satisfactory in giving single high-voltage impulses of low energy, free from oscillations. Constant watchfulness however was necessary, as the least poor contact or leak in any of the circuits immediately created an oscillation and thereby produced erratic results.

In Fig. 1, T is a high-potential transformer, with ratio of turns 1 to 300. Its high potential leads connect to the spark gap G. The screw thread of G is 1.6 mm. per turn, so that $\frac{1}{16}$ turn changes the gap by 0.1 mm.

At the low potential side, the transformer is shunted by an adjustable non-inductive resistance r_3, and connected through a second adjustable non-inductive resistance, r_2, to the continuous supply voltage e_2.

As a source of direct voltage there was used a 40-ampere 140-volt mercury arc rectifier R, supplied through the reactive transformer T_1 with 60-cycle 110-volt alternating current from the city lighting system. To suppress the voltage pulsations of the rectifier, a high reactance x_1, of about $L_1 = 1.0$ henry inductance, was inserted into the circuit, and the circuit then shunted by a condenser of about $C = 25$ mf. capacity. A non-inductive resistance r_1 was shunted across the voltage e_2, and adjusted so as to give a continuous load of $i_1 = 2.5$ amperes.

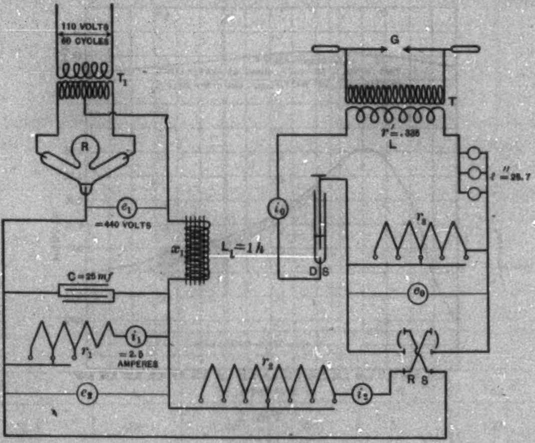

Fig. 1

In some tests, a non inductive resistance r'' was inserted, in series with the transformer. For this resistance, three incandescent lamps were used in multiple; one metallized filament lamp, and two luminous heater lamps. The combination of the positive temperature coefficient of the former, and the negative temperature coefficient of the latter gave a resistance which was nearly constant up to 4 amperes (about 400 watts), and at the same time extremely non-inductive. Its characteristic is shown in Fig. 2.

The impulse produced by closing the transformer circuit was used, as the impulse in opening the circuit is indefinite in voltage, and usually oscillatory. The circuit was closed by a drop switch *D S* Fig. 1; a 7-mm. copper rod dropping 30 cm. into a mercury cup. As the residual magnetism of the transformer exerts a considerable effect, the impulse was always produced by closing the circuit in the reverse direction from that in which it had been closed before. For this purpose the reversing switch *R S* was inserted between the shunt resistance r_3 and the series resistance r_2.

With $i_0 = 2$ amperes in the transformer *T*, and an inductance $L_1 = 0.75$ henry, the current in the condenser *C* was 0.12 ampere. As the frequency of the pulsation is 120 cycles, this gives,

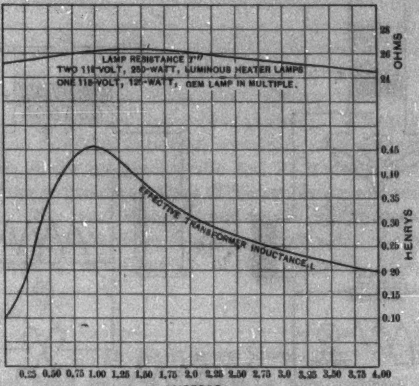

FIG. 2

for $L_1 = 1.0$ henry, a pulsation of 5 volts out of 440, or rather less, since part of the condenser current is due to higher harmonics. This pulsation did not extend into the transformer *T*, but the current pulsation in this transformer, read by a 1 to 1 transformer, was less than 0.01 ampere. To check the absence of any pulsation, after every set of tests the spark terminals *G* were slowly brought into contact with each other, and it was observed, whether at the moment before touching a continuous discharge was noticeable. This check was found very sensitive in discovering the beginning of any loose contact, leak, etc., in the system, before it exerted any appreciable effect on the readings.

TABLE I

October 4, 1909

Needles; Resistance

i_1	e_1	i_2	e_2	i_0	e_0
2.5	440	—	—	—	—
2.3	436	1.9	368	1.0	24
2.4	440	1.05	384	0	100
2.35	436	1.25	380	1.0	24

Dist. turns	No. of trials	No. of discharges
6	10	10
6½	10	10
7	10	10
7½	10	10
8	10	10
8½	10	10
8	10	8
9½	10	0
10	10	0
9½	10	0
9⅜	10	1
9¼	10	4
9⅛	10	7
9	10	9
8⅞	10	10
Continuous discharge 0		

i_1	e_1	i_2	e_2	i_0	e_0
2.4	436	1.05	384	0	100
2.35	436	1.25	380	1.0	24
2.5	440	—	—	—	—

e_0	dist. cm.
50	1.00
100	1.47
150	1.77
200	1.96
250	2.04
300	2.12
350	2.16

The method of operation was as follows: The resistances r_3 and r_2 were adjusted so that with the transformer circuit open, the voltage e_0, and with the transformer circuit closed, the current i_0, had predetermined values. All the meters e_1, e_2, e_0 and i_1, i_2, i_0 were read, with *R S* open, with *R S* closed and *D S* open, and with *R S* and *D S* closed. Then *R S* was opened, *D S* opened, *R S* closed in reverse direction, *D S* closed, while observing the gap *G*; then *R S* opened, *D S* opened, *R S* closed in reverse direction, etc., until 12 observations were made. Of these, the first two were not considered. The first setting of the gap was chosen so as to give a discharge at every impulse. Then the gap was lengthened and the tests repeated, and so on until no discharges passed. Then the gap was shortened in small steps, and again at every step 12 impulses observed, until every impulse passed. The gap terminals were next brought into contact to observe any continuous discharge, and then all the meters read once more, to insure that no change had taken place during the test. Ten seconds were allowed after every operation, to reach stationary conditions. The drop switch *D S* was never used for opening the circuit, and the mercury was frequently changed. A set of such tests is given in Table I.

By interpolation, the number of turns, that is, the length of gap, is found, at which 50 per cent of the impulses, that is, five out of ten, discharge across the gap.

Tests were made at the voltages $e_0 = 50$, 100, 150, 200, 250, 300 and 350, corresponding to the discharge voltages, by the ratio 1 to 300, of $e = 15$, 30, 45, 60, 75, 90 and 105 kilovolts, and with currents $i_0 = 0.25$, 0.5, 1.0, 2.0, 3.0 and 4.0 amperes. The complete set for $i_0 = 1.0$ amperes, of which the record of Table I is one point, is also given in Table I, and the various sets of tests made with needles in air, for $i_0 = 1.0$, are given in Table II. The different sets of tests are averaged.

TABLE II

Needles in air

e_0	$r'' = 0$ June '09	0 July '09	26 ohms Oct. '09	26 ohms Oct. '09	0 Oct. 09	Avg.
50	d —	—	1.00	1.00	0.94	0.98
100	—	1.46	1.47	1.44	1.50	1.47
150	1.79	1.71	1.77	1.80	1.77	1.77
200	1.94	1.92	1.96	1.92	2.00	1.95
250	—	2.08	2.04	2.01	2.09	2.06
300	2.17	2.10	2.12	2.10	2.16	2.13
350	—	2.17	2.16	2.17	2.24	2.19

An approximate theoretical discussion of the transient phenomena in the system of circuits Fig. 1 is given in the appendix. From this it follows that the transient voltage depends only upon the transformer inductance L, and on e_0 and i_0, but is independent of the resistance r in the transformer circuit. This affords a method of checking the absence of oscillations or other disturbances. The internal resistance of the transformer is $r' = 0.355$ ohm. Inserting a much larger resistance, $r'' = 25.7$ ohms, in series with the transformer circuit, should greatly decrease any oscillation in this circuit, if it existed, but should have no effect if the transient voltage is a single impulse, in accordance with the discussion in the appendix. All the tests were made with and without this additional resistance r'', and the agreement of the results of both sets of tests shows the absence of oscillations.

III. Results of Tests

Tests were made with needles, and with spheres of 3.8 cm. diameter, in air and in dry white paraffine oil. For the latter, the spark gap was arranged vertically, and surrounded by a glass vessel filled with oil.

TABLE III

Transient voltages—Dielectric strength of air

Voltage		Amperes primary supply i_0 =						
Primary volts e_0	Secondary kilovolts e	0.25	0.50	1.0	2.0	3.0	4.0	(∞)
Needles		Striking Distance in cm.						
50	15	0.41	0.75	0.98	1.10	—	1.22	1.26
100	30	0.48	0.88	1.47	1.89	—	2.31	2.73
150	45	0.50	0.97	1.77	2.44	2.68	3.14	4.45
200	60	0.515	1.02	1.95	2.88	3.32	3.88	6.83
250	75	0.52	1.05	2.06	3.22	—	4.50	9.86
300	90	0.525	1.06	2.13	3.45	4.05	5.02	13.0
350	105	0.53	1.07	2.19	3.60	4.46	5.39	16.3
Without resistance..........		1	1	3	2	1	1	—
With resistance............		1	1	2	1	0	1	—
Spheres								
50	15	0.075	0.18	0.29	0.36	0.38	0.40	0.43
100	30	0.093	0.235	0.47	0.66	0.73	0.78	0.95
150	45	0.106	0.265	0.57	0.90	1.02	1.16	1.54
200	60	0.11	0.285	0.65	1.07	1.27	1.49	2.19
250	75	0.11	0.30	0.69	1.19	1.40	1.70	2.86
300	90	0.11	0.31	0.715	1.29	1.50	1.87	—
350	105	0.11	0.32	0.73	1.35	1.56	1.94	—
Without resistance..........		2	2	3	2	1	1	—
With resistance............		1	1	2	1	0	1	—

The results are given in Table III and Figs. 3 and 4 for air, and in Table IV and Figs. 5 and 6 for oil. In these tables also are given the number of sets of tests, with the resistance r'', and without it, which have been averaged as discussed above.

TABLE IV
Transient voltages—Dielectric strength of paraffine oil

Voltage		Amperes primary supply i_0 =				
Primary volts e_0	Secondary kilovolts e	0.50	1.0	2.0	4.0	(∞)
Needles		Striking Distances in cm.				
50	15	0	0	0	0	0.03
100	30	0	0	0.016	0.054	0.17
150	45	0	0.025	0.064	0.21	0.49
200	60	0	0.036	0.155	0.40	0.98
250	75	0	0.049	0.235	0.54	—
300	90	0	0.055	0.28	0.64	—
350	105	0	0.061	0.30	0.71	—
Without resistance.......		1	2	1	1	—
With resistance..........		1	2	1	1	—
Spheres						
50	15	0.026	0.042	0.050	0.066	0.07
100	30	0.033	0.061	0.071	0.098	0.16
150	45	0.036	0.071	0.087	0.121	0.27
200	60	0.037	0.078	0.099	0.133	0.375
250	75	0.037	0.083	0.107	0.144	0.48
300	90	0.037	0.088	0.114	0.157	—
350	105	0.037	0.092	0.120	0.163	—
Without resistance.......		2	4	2	2	—
With resistance..........		2	4	2	2	—

For comparison, tests were made with 60-cycle alternating voltages and are given in Table V and Fig. 7, for needles and spheres, in air and in oil.

In these tests, the primary of the transformer was shunted by a constant non-inductive resistance of 30 ohms, to avoid any change of wave-shape of the terminal voltage of the transformer when varying it by a series resistance. The constancy of the transformer ratio was checked by using another like transformer as a step-down transformer. For needle points in air, the observed striking distances were identical, within the errors of observation, with those given in the Standardization Rules of the A.I.E.E.

TABLE V

Alternating-current 60-cycle voltages—Dielectric strength

Kilovolts maximum = $\sqrt{2}$ × effective voltage	Striking distance in air-cm.		Striking distance in paraffin oil—cm.	
	Needles A. I. E. E.	Spheres	Needles	Spheres
5	0.40	0.125	—	0.02
10	0.81	0.27	—	0.045
15	1.26	0.43	0.03	0.07
20	1.72	0.59	0.06	0.10
25	2.22	0.76	0.11	0.13
30	2.73	0.95	0.17	0.16
35	3.27	1.14	0.27	0.20
40	3.82	1.34	0.37	0.235
45	4.45	1.54	0.49	0.27
50	5.19	1.75	0.63	0.305
55	5.98	1.96	0.80	0.34
60	6.83	2.19	0.98	0.375
65	7.75	2.41	—	0.41
70	8.70	2.63	—	0.445
75	9.80	2.86	—	0.48

In the last columns of Table III and IV, and in Figs. 3 to 6, have been added the striking distances for maximum alternating voltage, that is $\sqrt{2}$ times effective voltage, as taken from Table V and Fig. 7.

It is interesting to note in Table V and Fig. 7 the great difference in the shape of the curves of striking distances, with 60-cycle alternating voltage, in oil and in air. In oil, up to 29 kilovolts maximum, the striking distance between needle points is less than between 3.8 cm. spheres. Below 15 kilovolts, no striking distance between needle points under oil could be observed at all; the striking distance apparently was so small that the needle points could not be adjusted for a sufficiently small gap. When approaching the disruptive voltage, mechanical motion of the oil and, occasionally, the production of gas bubbles was observed, and also a noticeable time lag, so that three to five seconds had to be allowed at every voltage point before further raising the voltage; otherwise the disruptive voltage could be considerably exceeded. It seems that electrostatic disruption in oil is a very complex phenomenon, involving mechanical motions and chemical dissociation. The oil had to be carefully dried and filtered, otherwise the results become very erratic.

In Figs. 3 and 4, the striking distances with transient voltages, between needles and 3.8-cm. spheres in air, each curve corresponds to a definite current input into the transformer, that is, a definite energy value. The energy is the lower, the smaller the current and the curve for unlimited energy input, as given by a steadily applied alternating voltage, is marked by ∞.

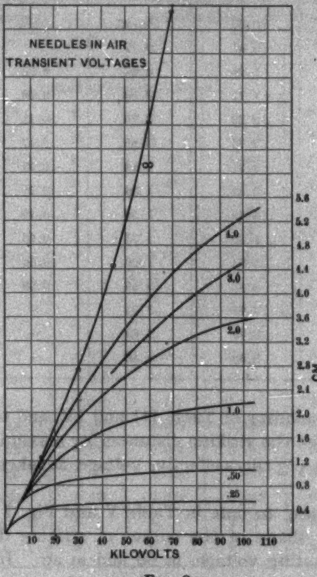

Fig. 3

It seems from this that the curves of striking distances with transient voltages start from the curve of unlimited energy (∞) at low voltages, but drop below this curve the earlier and the more rapidly, the smaller is the amount of available energy.

In Fig. 3, for an energy input into the transformer represented by $i_0 = 0.25$ or 0.5 ampere, the striking distance is, at 15 kilovolts, very much lower than at unlimited energy. At $i_0 = 1.0$ and 2.0 amperes it is still appreciably lower, while for $i_0 = 4.0$ amperes, it is practically the same at 15 kilovolts as with unlimited energy, but drops below at higher voltages.

All these curves of constant-energy striking distance seem, for higher voltages, to approach the horizontal direction; that is, a finite limit of striking distance. For the small amount of energy available with $i_0 = 0.25$ and $i_0 = 0.5$ ampere, this final limit of striking distance seems to have been practically reached within the range of the tests, and has been fairly well approached at $i_0 = 1.0$ ampere. For $i_0 = 2.0$ amperes or more, however, the curve of striking distance is still markedly rising at 105 kilovolts.

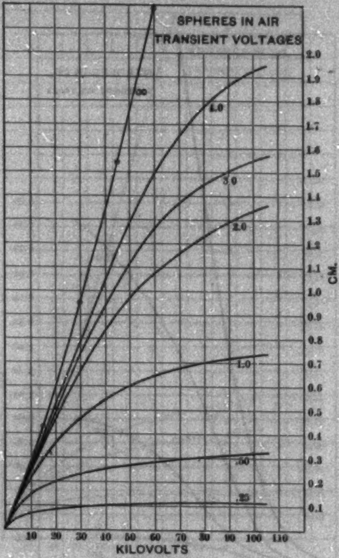

FIG. 4

With transient voltages, the striking distance seems to approach a finite limit with increasing voltage, and this limit is the higher, the greater is the available energy, which is behind the voltage. For sufficiently high voltage, the striking distance at limited energy becomes independent of the voltage, and merely a function of the energy back of the voltage. Thus between needle points in air, for the energy represented by $i_0 = 0.25$ ampere, 50 kilovolts gives practically the same striking distance as 100 kilovolts—a little over one-half cm., At the higher energy given by $i_0 = 0.5$ ampere, 50 kilovolts still gives nearly the same striking distance as 100 kilovolts, but the striking distance is about twice as great as at the lower energy given by $i_0 = 0.25$ amperes. At 25 kilovolts, $i_0 = 0.25$ ampere gives nearly the same striking distance as at 100 kilovolts, but $i_0 = 0.5$ ampere already gives a lower striking distance at 25 than at 100 kilovolts.

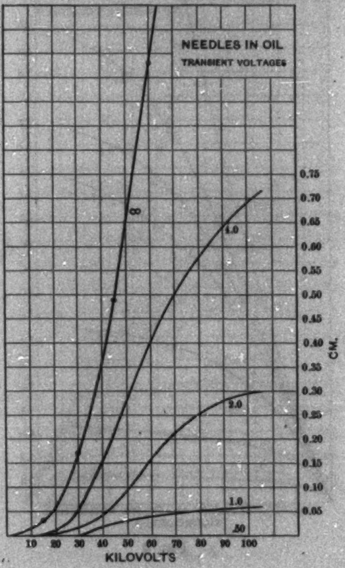

Fig. 5

Hence the usual curve of striking distance, derived by tests with unlimited energy, does not apply at all when the voltage lasts so short time that the energy back of the voltage is limited. At 100 kilovolts, the striking distance between needle points in air is about 15 cm. with unlimited energy, but only 0.52 cm., or about one-thirtieth as much, with the limited power of $i_0 = 0.25$ ampere; and even at $i_0 = 1$ ampere, the striking distance is still less than 2.2 cm., or one-seventh as much as given by unlimited energy at the same voltage of 100 kilovolts.

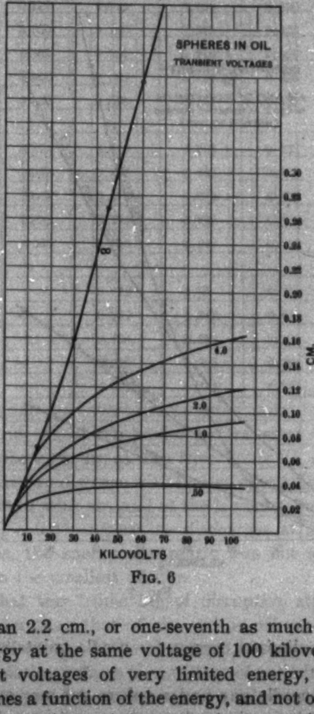

Fig. 6

At transient voltages of very limited energy, the striking distance becomes a function of the energy, and not of the voltage, and increases with increasing energy, but not with increasing voltage.

Between spheres in air, the effect of limited energy back of the voltage in decreasing the striking distance is similar to that between needle points, but is greater with low values, and slightly less with higher values of energy. That is, with the same available energy, if the energy is very small, the striking distance between spheres at transient voltage is a smaller fraction of the striking distance of unlimited energy, than it is with needle points. This is shown by Table VI, which gives the striking distances of transient voltages as fractions of the striking distances with unlimited energy, for needle points and for 3.8-cm spheres in air.

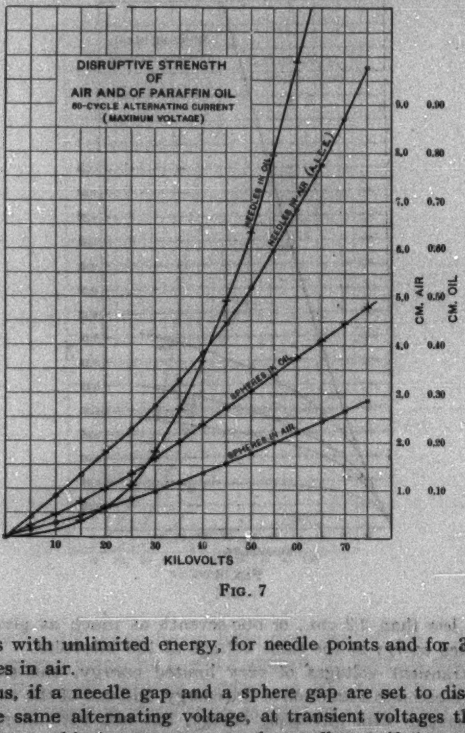

FIG. 7

Thus, if a needle gap and a sphere gap are set to discharge at the same alternating voltage, at transient voltages the discharges would always pass over the needle gap if the energy is very small, and usually over the sphere gap if the energy is large.

TABLE VI

Transient-voltage striking distances in air, as fractions of unlimited-energy striking distances

Voltage kilovolts e	$i_0 = 0.25$	0.50	1.0	2.0	4.0
Needles in air:					
15	$\frac{d}{e} = 0.325$	0.595	0.777	0.873	0.970
30	0.176	0.323	0.538	0.693	0.845
45	0.112	0.218	0.398	0.500	0.707
60	0.706	0.150	0.286	0.422	0.567
75	0.053	0.107	0.210	0.329	0.460
90	0.040	0.082	0.164	0.266	0.387
105	0.033	0.066	0.134	0.221	0.331
Spheres in air					
15	0.174	0.418	0.675	0.837	0.930
30	0.098	0.247	0.495	0.695	0.823
45	0.069	0.172	0.370	0.585	0.754
60	0.050	0.130	0.297	0.488	0.680
75	0.038	0.105	0.242	0.416	0.595
Spheres in oil:					
15		0.372	0.60	0.715	0.940
30	—	0.207	0.382	0.445	0.613
45	—	0.134	0.263	0.322	0.448
60	—	0.099	0.208	0.264	0.355
75	—	0.077	0.173	0.223	0.300

With spheres in oil, the behavior at transient voltages is similar as with spheres in air, as seen from Table VI, except that the decrease of striking distance with limited energy is very much greater with oil than with air, and at the lowest value of energy, that given by $i_0 = 0.25$ ampere, no discharges at all could be observed; that is, the energy apparently was not sufficient to break down even the smallest oil film.

This means that the "time lag of disruptive strength" of oil is much greater than that of air, and an oil gap requires a greater amount of energy, to be punctured, than an air gap set for the same alternating voltage (*i.e.*, voltage of unlimited energy.)

Thus a sphere gap of 0.6 cm. in air, and a sphere gap of 0.1 cm. in oil, discharge at the same voltage of 20 kilovolts, if unlimited power is back of the voltage. With a single impulse of transient voltage, limited in energy to that given by $i_0 = 2.0$ amperes, the air gap discharges at 27 kilovolts, while the oil gap requires

62 kilovolts. To discharge at 30 kilovolts, the energy given by $i_0 = 4.0$ amperes is required for the oil gap, while the air gap requires only the energy given by about 1.75 amperes; that is, much less energy. It therefore follows, that an air gap, set for such distance as to protect oil insulation against voltages of unlimited energy, also protects against transient voltages; but inversely, an oil gap, even if set to discharge at an alternating voltage much lower than that which air insulation would safely stand, would not protect against transient voltages if of sufficiently limited power.

To some extent, similar relations exist between the needle gap and sphere gap in air. As seen from Table VI, for low values of energy, an air needle gap would protect a sphere gap against transient voltages, but not inversely; while for higher values of energy, a sphere gap would protect a needle gap against transient voltage, but not inversely. The differences for higher values of transient energy are relatively small compared with those for lower values, and in general, therefore, it seems that the needle gap in air is safer than the sphere gap in protecting against transient voltages. Thus spark gap terminals are preferably corrugated or knurled.

Very different and strange are the curves of striking distance of transient voltages, with needle points in oil, as shown in Fig. 5. The lower energy values, corresponding to $i_0 = 0.25$ and $i_0=0.5$ ampere, give no appreciable striking distance at all, even above 100 kilovolts. At $i_0 = 1.0$ ampere, no appreciable striking distance exists at 30 kilovolts, but the lowest voltage at which an appreciable though very small (0.025 cm.) striking distance is observed, is at 45 kilovolts. Even at the highest energy values used in the test, 15 kilovolts give no striking distance. With needle points in oil, the transient voltage curve does not approach the alternating voltage curve ∞ at low voltage (as seems to be the case in Figs. 3, 4 and 6). It has an incurve at low voltage like the alternating curve ∞, but at higher voltages, the higher the voltage the lower the energy. Such needle points in oil seem to require the highest amount of energy; that is, they give the greatest time lag of discharge, far greater than spheres in oil. At 60 kilovolts, the striking distance between needle points in oil is, at $i_0 = 1.0$ ampere, less than 1/27 of what it is with unlimited energy, while with spheres in oil it is about one-fifth, and with needles as well as spheres in air, approximately three-tenths.

There appears thus an essential difference in the relation between needle points and spheres as discharge terminals in oil and in air, and the difference is of the same general character for transient voltages as for alternating voltages. This difference is somewhat similar in its nature to the difference between brittle and ductile bodies in their action against mechanical forces.

IV. Striking Distances with Infinite Transient Voltages

The striking distances of transient voltages of constant energy seem, with increasing voltage, to approach a constant value, as seen in Figs. 3 to 6. An attempt was therefore made to find a mathematical expression for this upper range of the curve, at which the striking distance begins to become independent of the voltage and a function of the energy. The two simplest curves, which respresent asymptotic approach to a straight line, are the exponential and the hyperbola. The shape of the curves in Figs. 3 to 6 is different from the characteristic of the exponential, and an equilateral hyperbola was thus tried.

Assuming that d_0 = the striking distance, reached at infinite transient voltage, and the approach to this value is hyperbolic at higher voltages. This would give the curve

$$e\,(d_0 - d) = c^2 \qquad (1)$$

where d is the striking distance at transient voltage e, and c is a constant.

If now e_1 and e_2 are two voltage values, and d_1 and d_2 their corresponding striking distances, we get, by substitution in equation (1)

$$e_1\,(d_0 - d_1) = c^2$$

$$e_2\,(d_0 - d_2) = c^2$$

and from this, by eliminating c^2

$$d_0 = \frac{e_2\,d_2 - e_1\,d_1}{e_2 - e_1} \qquad (2)$$

By this equation (2), from any two points of a curve a value of d_0 can be calculated, and if the values of d_0, calculated from the different pairs of points of the same curve of striking distances agree, this would show an agreement of the observed curve with an equilateral hyperbola.

This calculation was made by using the observations from 45 to 105 kilovolts, and the results are given in Table VII.

TABLE VII
Striking distances d_0 at infinite transient voltage

$$e\,(d_0 - d) = c^2; \quad d_0 = \frac{e_2\,d_2 - e_1\,d_1}{e_2 - e_1}$$

	i_0	$e_1 = 45$ $e_2 = 60$	45 75	75 90	90 105	kilovolts kilovolts
Needles in air:	0.25	0.56	0.54	0.55	0.56	avg. d_0 = 0.55
	0.5	1.17	1.17	1.11	1.13	1.14
	1.0	2.49	2.50	2.48	2.55	2.51
	2.0	(4.20)	4.58	4.60	4.50	4.56
	4.0	(6.10	6.98)	7.42	7.61	7.5
Spheres in air:						
	0.25	—	—	—	—	Avg. d_0 = 0.11
	0.5	0.345	0.36	0.36	0.38	0.36
	1.0	(0.89)	0.85	0.84	0.82	0.84
	2.0	(1.58)	1.67	1.79	1.71	1.72
	4.0	2.48	2.54	2.72	2.36	2.52
Needles in oil:						
	1.0	(0.067)	0.11	0.085	0.096	Avg. d_0 = 0.09
	2.0	0.43	0.555	0.505	0.42	0.46
	4.0	(0.97)	1.1	1.14	1.13	1.13
Spheres in oil:						
	0.5	—	—	—	—	Avg. d_0 = 0.037
	1.0	(0.909)	0.103	0.113	0.116	0.111
	2.0	(0.135)	0.139	0.149	0.156	0.148
	4.0	(0.169)	0.188	0.222	0.199	0.203

Four values of d_0, corresponding to successive sections of the empirical curve, are given, and as seen from Table VII, these four successive values of d_0 agree with each other very well, especially in air; that is, they show no regular deviation from the averages, which are also given in Table VII. A marked deviation from the average is found only for the lower voltage sections of the curves of high energy; that is, those parts at which the curve is fairly close to that of unlimited energy, and was to be expected in this

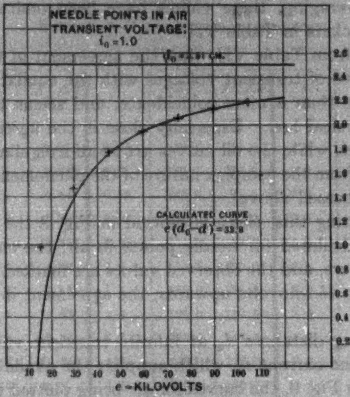
NEEDLE POINTS IN AIR
TRANSIENT VOLTAGE:
$i_0 = 1.0$
$d_0 = 2.51$ CM.
CALCULATED CURVE
$e(d_0 - d) = 32.8$
d = CM.
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
10
20
30
40
50
60
70
80
90
100
110
e = KILOVOLTS

FIG. 8

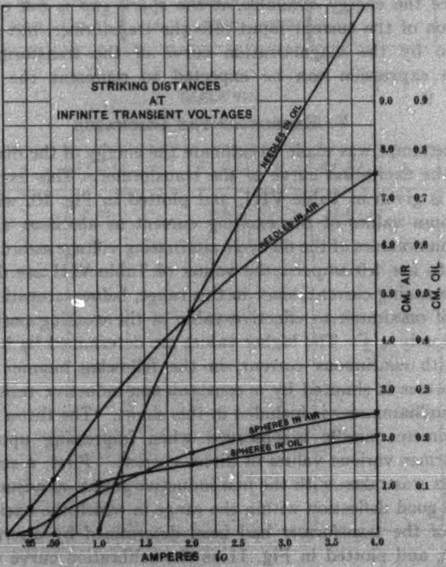
STRIKING DISTANCES
AT
INFINITE TRANSIENT VOLTAGES
NEEDLES IN OIL
NEEDLES IN AIR
SPHERES IN AIR
SPHERES IN OIL
9.0
0.9
8.0
0.8
7.0
0.7
6.0
0.6
5.0
0.5
4.0
0.4
3.0
0.3
2.0
0.2
1.0
0.1
CM. AIR
CM. OIL
.25
.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
AMPERES i_0

FIG. 9

case. In averaging, these values have been omitted and are given in brackets in Table VII.

It seems, from Table VII, that the agreement of the striking distance curve of transient voltages with the equilateral hyperbola, is more than a mere coincidence, and seems to be based on some physical law. Especially close is the agreement with the air curves, while the oil curves are more irregular, as was to be expected from the complex nature of the phenomena occurring in oil, as discussed above.

As illustrating this, there is plotted in Fig. 8 the equilateral hyperbola calculated for needle points in air, the energy being $i_0 = 1.0$ ampere, and the observed values are marked by crosses. As seen, from 45 kilovolts upwards, the agreement is practically perfect.

The striking distances d_0 at infinite transient voltage, as a function of the current i_0, which supplies the available energy, are plotted in Fig. 9, the curves for air being plotted to 10 times the scale of the curves for oil, as in Fig. 7.

Since the energy available at the spark gap is not a simple function of the current input into the transformer, but related thereto by the magnetization curve of the transformer, no simple expression can be expected to represent the curves of Fig. 9.

V. Energy of the Discharge

An attempt was made to estimate the energy of the discharge from the excitation curve of the transformer. This excitation curve is given in Table VIII, and plotted in Fig. 10, with the maximum values of the exciting current as abscissæ, and the maximum values of the 60-cycle alternating voltage as ordinates.

Up to $i = 1.0$ ampere, the values of Table VIII are derived by alternating current, since in this range, below saturation, the ratio of maximum to effective value of the exciting current is very closely $\sqrt{2}$. The higher values are determined by ballistic test with continuous current, in the following manner: The transformer is shunted by a constant non-inductive resistance, and a milliammeter is included in this shunt. The throw of the milliammeter needle is observed when impressing upon the transformer various values of direct current. First, a series of readings was taken with the non-inductive shunt so adjusted as to give good deflection within the range in which the excitation curve of the transformer had been determined by alternating current, and plotted in Fig. 11 as the calibration curve of the

TABLE VIII

Excitation of transformer and energy

60 Cycles

i	e	$\Sigma i \Delta e = s$	i	e	$\Sigma i \Delta e = s$	i	e	$\Sigma i \Delta e = s$
0.05	2.1	0.052	0.75	119.6	54.2	1.9	233	189.4
0.1	4.7	0.247	0.8	130.1	62.4	2.0	237	197.2
0.15	7.9	0.647	0.85	140.6	71.1	2.2	245	214.0
0.2	12.2	1.397	0.9	151.0	80.2	2.4	253	232.4
0.25	18.3	2.767	0.95	161.5	89.9	2.6	260	249.9
0.3	26.4	4.99	1.0	171.8	100.0	2.8	267	268.8
0.35	36.2	8.18	1.1	185.0	121.0	3.0	273	286.2
0.4	46.2	11.93	1.2	195.0	132.5	3.2	279	304.8
0.45	56.5	16.50	1.3	203.0	142.5	3.4	284	321.3
0.5	66.9	21.24	1.4	210.0	152.0	3.6	289	338.8
0.55	77.4	26.8	1.5	216.0	160.7	3.8	294	357.3
0.6	88.0	32.9	1.6	221.0	168.4	4.0	299	376.8
0.65	98.5	39.4	1.7	225.0	175.0			
0.7	109.1	46.6	1.8	229.0	182.0			

TABLE VIII

Correction for residual magnetism

i	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$	e	$\Sigma i \Delta e = s$
i_0 =		0.25		0.5		1.0		$\geqq 2.0$
0.0	-8.0	0.0	-40	0	-124	0	-168	0
0.05	-4.2	0.095	-26	0.35	- 68	1.40	-104	1.60
0.1	0	0.410	-14	1.25	- 41	3.42	- 58	5.05
0.15	+5.8	1.135	- 4	2.50	- 20	6.04	-26	9.05
0.2	11.5	2.135	+ 7	4.42	- 4	8.84	- 6	12.55
0.25	18.3	3.675	17	6.57	+10	11.99	+10	16.15
0.3			26.4	9.15	23	15.57	23	19.73
0.35			etc.		34	19.15	34	23.31
0.4					46.2	23.73	46.2	27.89
					etc.		etc.	
s, by above table =		2.767		4.99		11.93		11.93
Difference =		0.908		4.16		11.8		15.96

TABLE IX
Energy of magnetization

i_0 = (amperes) =	0.25	0.5	1.0	2.0	3.0	4.0
$s = \Sigma i \Delta e$ =	2.767	21.24	100.0	197.2	286.2	376.8
Correction for residual magnetism =	0.908	4.16	11.8	15.96	15.96	15.96
Per cent =	32.8	19.6	11.8	8.1	5.6	4.2
Total s =	3.675	25.4	111.8	213.2	302.2	392.8
Energy, in joules:						
$W = \frac{s}{2\pi f} = \frac{s}{377}$ =	0.00975	0.0676	0.298	0.566	0.803	1.044
=	0.01	0.068	0.30	0.566	0.80	1.04

(f = 60 cycles.)

ballistic test. Then the non-inductive resistance was adjusted to bring the deflection for the range from 1.0 ampere to 4.0 amperes, on the curve Fig. 11, and from this curve, from the known voltage at 1.0 ampere, the voltages corresponding to higher currents were calculated.

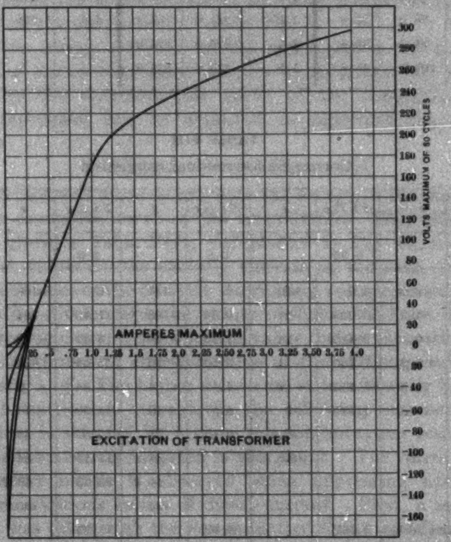

FIG. 10

By energizing the transformer in the same direction as before, and in the reverse direction, the residual magnetism was determined, and thereby the correction of the energy for residual magnetism estimated.

The energy input into the transformer was calculated from the area between the excitation curve Fig. 10 and the vertical axis, as

$$W = \frac{\Sigma i \triangle e}{2 \pi f}$$

where $\triangle e$ is the difference between two successive voltage values, i the average current corresponding to $\triangle e$, and thus $\Sigma i \triangle e$ the desired area. $f = 60$ cycles.

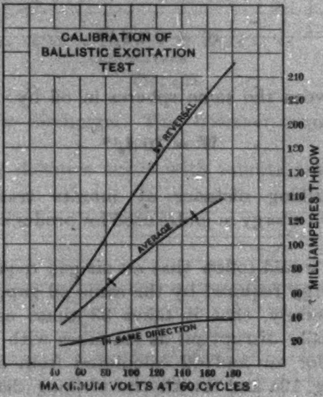

Fig. 11

This calculation is given in Tables VIII and IX, together with an approximate correction for residual magnetism.

It is interesting to note, that the energy values used in the tests, varied from a minimum of 0.01 joule (or watt-seconds) to a little over 1 joule. It must be considered, however, that this represents the total energy input into the transformer. These energy values, therefore are the upper limit of the energy which is sufficient to break down the spark gap, and considered in this manner, it is remarkable to see how very small an amount of energy is sufficient to produce disruptive effects.

Comparing the striking distances at infinite transient voltage (that is, at voltages which are so high, that the striking distance has become independent of the voltage, and a function of the energy only), as given in Table VII, with the corresponding values of energy, in Table IX, would give the striking distance as a function of the energy. The data are not sufficient to determine with any degree of exactness the dependence of the striking distance on the energy, since the energy values represent the total energy, and not that available at the spark gap. By comparing, however, the curves of striking distance for oil, and those for air, with the same terminals, relative values of the disruptive energy of oil and of air can be derived.

The striking distances between 3.8-cm. spheres in air can be represented approximately by

$$W = 0.3\, d_0^{1.5}$$

and those between the same spheres in oil by:

$$W = 10\, d_0^{1.5}$$

where d_0 = striking distance at infinite transient voltage, in cm., and W = energy in joules used for producing the transient voltage.

From this it would follow that an air gap requires only 3 per cent of the energy required by the same oil gap, to start a discharge; or inversely, that it takes 33 times as much energy to electrostatically disrupt oil as its takes with air.

The curves for air and oil calculated from above equation are given in Fig. 12a and b with the striking distance between spheres d_0 as abscissæ, and the energy W was ordinates. The observed values are marked by crosses, but as seen, the agreement is not very close.

The striking distance curve with transient voltages between needle points in oil is so different in shape from that in air that it does not appear probable that both can be expressed by the same equation, as required for comparing the disruptive energy of air and oil. The striking distance curve between needle points in oil, seems to reach the zero value ($d_0 = 0$) at a finite value of energy ($W_0 = 0.235$ joule), and if this is the case, it would mean, that with needle points in oil, about one quarter joule is required to start the discharge, irrespective of distance and voltage, and only the remainder of the energy is available for disrupting the path of the discharge. This however requires further investigation.

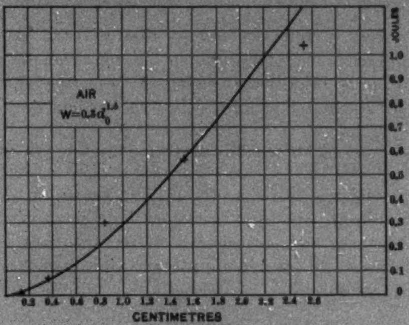

Fig. 12A

The striking distance curve with infinite transient voltages between needle points in air can be expressed approximately by the equation

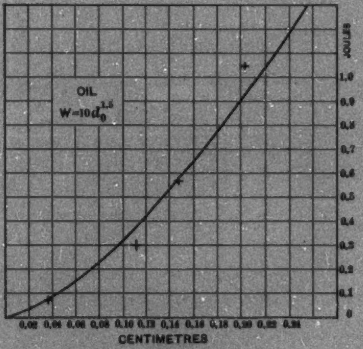

Fig. 12B

$$W = 0.063\, d_0^{1.5}$$

and that between needle points in oil, by the equation

$$W = 0.235 + 0.72\,d_0$$

From this it would also follow, that a spark gap between 3.8-cm. spheres in air requires about 5 times as much energy as a spark gap of the same length in air between needle points.

In table X are given the ratios of the striking distances $\left(\frac{\text{distance in oil}}{\text{distance in air}}\right)$ for needle points and for 3.8-cm. spheres.

As seen, with needle points the ratio increases with increasing transient voltage, and also increases with increasing energy. With spheres, the ratio first decreases, and then increases again, and seems to reach a minimum for some intermediate values of voltage and of energy.

TABLE X

Ratio of striking distances = $\frac{\text{distance in oil}}{\text{distance in air}}$

e kilovolts	amperes = 0.25 joules = 0.01	0.50 0.068	1.0 0.30	2.0 0.566	4.0 1.04	8 8
Needles						
15	0	0	0	0	0	0.0238
30	0	0	0	0.0085	0.0234	0.0623
45	0	0	0.0141	0.0262	0.067	0.110
60	0	0	0.0185	0.0538	0.103	0.144
75	0	0	0.0238	0.0730	0.120	—
90	0	0	0.0258	0.0812	0.128	—
105	0	0	0.0278	0.0833	0.132	—
∞	0	0	0.0358	0.101	0.151	—
Spheres						
15	0	0.144	0.145	0.139	0.165	0.163
30	0	0.141	0.130	0.108	0.126	0.168
45	0	0.136	0.125	0.097	0.104	0.182
60	0	0.130	0.120	0.093	0.089	0.172
75	0	0.123	0.120	0.090	0.085	0.168
90	0	0.119	0.124	0.088	0.084	—
105	0	0.116	0.126	0.089	0.084	—
∞	0	0.103	0.132	0.086	0.081	—

VI. CONCLUSIONS

The disruptive discharge through a dielectric requires not merely a sufficiently high voltage, but requires a definite minimum amount of energy.

The disruptive discharge does not occur instantly with the application of voltage, but a finite though usually very small time elapses after the application of voltage, before the discharge occurs. During this time the disruptive energy is supplied to the dielectric. This time may be called the "time lag of the discharge".

The disruptive energy of oil seems to be about 30 times greater than that of air, and that of solid dielectrics probably is still greater. An oil gap thus requires a greater time before it discharges than an air gap, but even an air gap does not discharge instantly. An air gap thus can protect an oil gap against momentary voltages, but not inversely.

With limited available energy, the striking distance increases slower with increasing voltages, and drops below the striking distance with unlimited energy; and ultimately the striking distance becomes entirely independent of the voltage, and merely a function of the energy.

At constant energy, with increasing voltage, the striking distance seems to approach constancy in a hyperbolic curve.

The voltage at which the striking distance has become practically independent of the voltage, is the lower, the more limited is the amount of available energy.

From the available data, the following approximate empirical equations for the energy W, in joules, used for a disruptive discharge over a distance d_0, in cm., are derived:

Needle points in air .... $W = 0.063\, d_0^{1.6}$
3.8-cm. spheres in air .... $W = 0.3\, d_0^{1.6}$
Needle points in dry white paraffine oil .... $W = 0.235 + 0.72\, d$
3.8-cm. spheres in dry white paraffine oil .... $W = 10\, d^{1.6}$

The investigation of the disruptive effects with transient voltages, *i.e.*, limited energy, is of theoretical interest, as it may lead to a clearer understanding of the nature of the disruptive discharge. It also is of industrial importance, as most of the abnormal voltage phenomena occurring in electric circuits are transient, *i.e.*, of limited energy, and an effective control and protection of electric systems therefore will require a knowledge of the action of transient voltages as well as permanent voltages. Very little however is known on the disruptive effect of transient voltages, and further extensive investigations on this subject are therefore desirable.

APPENDIX

APPROXIMATE EQUATIONS OF TEST CIRCUIT

Let $r = r' + r''$ = total resistance of transformer circuit, including lamp resistances, etc., and L = inductance.

Let e_0' = voltage impressed upon this circuit, with initial value e_0.

i = current in this circuit, with final value i_0

e = voltage induced in the transformer.

From Fig. 1 we have

$$e_2 = e_0' + r_2\, i_2 \tag{1}$$

$$e_0' = e + r\, i \tag{2}$$

$$e_0' = r_3\, (i_2 - i) \tag{3}$$

$$e = L \frac{d\, i}{d\, t} \tag{4}$$

Eliminating e_0', e, i_2, and substituting

$$R^2 = r\, r_2 + r\, r_3 + r_2\, r_3 \tag{5}$$

gives

$$L \frac{d\, i}{d\, t} + \frac{R^2}{r + r_2}\, i - \frac{r_3}{r_2 + r_3}\, e_2 = 0$$

and since, at the moment of starting, $t = 0$

$$i = 0, \text{ hence } \quad e_0 = \frac{r_3}{r_2 + r_3}\, e_2. \tag{6}$$

the equation becomes

$$L \frac{d\, i}{d\, t} + \frac{R^2}{r + r_3}\, i - e_0 = 0 \tag{7}$$

This is integrated by

$$i = A\, \epsilon^{-a t} + B \tag{8}$$

Substituting (8) in (7) gives

$$a = \frac{R^2}{(r+r_2)\ L} \tag{9}$$

$$B = \frac{e_0\ (r+r_2)}{R^2} \tag{10}$$

Since for $t = 0$, $i = 0$, we have, by substituting (9) and (10) in (8)

$$A = -B = -\frac{e_0\ (r+r_2)}{R^2} \tag{11}$$

Since for $t = \infty$, $i = i_0$, we have, by substituting in (8)

$$B = i_0 \tag{12}$$

hence, from (11) and (9)

$$A = -i_0 \tag{13}$$

$$a = \frac{e_0}{i_0 L} \tag{14}$$

thus

$$i = i_0 \left\{1 - \varepsilon^{-\frac{e_0}{i_0 L}t}\right\} \tag{15}$$

and from (4)

$$e = e_0\, \varepsilon^{-\frac{e_0}{i_0 L}t} \tag{16}$$

hence, for $t = 0$

$$e = e_0 \tag{17}$$

that is, the ratio of transformation holds for the initial transient voltage.

The time integral of voltage is

$$E = \int_0^\infty e\,dt$$

$$= i_0 L \tag{18}$$

and the equivalent duration of the transient voltage

$$t_0 = \frac{E}{e_0} = \frac{i_0 L}{e_0} \tag{19}$$

As seen, all resistances, r, r_2, r_3 are eliminated except insofar as they are contained in e_0, the initial voltage, and i_0, the final current.

The above equations are approximate only, since they assume e_2 and L as constants.

The values of t_0 are, for

i_0 =	0.25	0.50	1.0	2.0	3.0	4.0	amperes.
L =	0.194	0.354	0.455	0.314	0.242	0.198	henry
e_0 = 50	t_0 = 0.97	3.54	9.10	12.6	14.5	15.8	milli-secs.
100	0.48	1.77	4.55	6.3	7.2	7.9	" "
150	0.32	1.18	3.03	4.2	4.8	5.3	" "
200	0.24	0.88	2.27	3.15	3.6	3.95	" "
250	0.19	0.71	1.82	2.5	2.9	3.2	" "
300	0.16	0.59	1.52	2.1	2.4	2.6	" "
350	0.14	0.51	1.30	1.8	2.1	2.3	" "

that is, a time varying from 0.00014 to 0.0158 seconds

From the table of effective duration t_0 of the high voltage impulses, given at the end of the appendix, we can derive approximate values of the striking distances as function of the time of the application of constant voltage, by substituting the values of transient striking distances, given in Tables III and IV, into the Table X at the end of the appendix.

This gives the Table XII, which is plotted in Figs. 13 to 16. As seen, the curves have a curious double bend. This however

TABLE XII
Striking Distances with Transient Voltages
(From Tables III, IV and X)

	kv.									
	15	$t=$	0.97	3.54	9.10	12.6	14.5	15.8	$\times 10^{-3}$	∞
Air: Needles......		$d=$	0.41	0.75	0.98	1.10	—	1.22		1.26
Spheres......			0.075	0.18	0.29	0.36	0.38	0.40		0.43
Oil: Needles......				0	0	0		0		0.03
Spheres......				0.026	0.042	0.050		0.066		0.07
	30	$t=$	0.48	1.77	4.55	6.3	7.2	7.9		∞
Air: Needles......		$d=$	0.48	0.88	1.47	1.89	—	2.31		2.73
Spheres......			0.093	0.235	0.47	0.66	0.73	0.78		0.95
Oil: Needles......				0	0	0.016		0.054		0.17
Spheres......				0.033	0.061	0.071		0.098		0.16
	45	$t=$	0.32	1.18	3.03	4.2	4.8	5.3		∞
Air: Needles......		$d=$	0.50	0.97	1.77	2.44	2.68	3.14		4.45
Spheres......			0.106	0.265	0.57	0.90	1.02	1.16		1.54
Oil: Needles......				0	0.024	0.064		0.21		0.48
Spheres......				0.036	0.071	0.087		0.121		0.27
	60	$t=$	0.24	0.88	2.27	3.15	3.6	3.95		∞
Air: Needles......		$d=$	0.515	1.02	1.95	2.88	3.32	3.88		6.83
Spheres......			0.11	0.285	0.65	1.07	1.24	1.49		2.19
Oil: Needles......				0	0.036	0.155		0.40		0.98
Spheres......				0.037	0.078	0.099		0.133		0.375
	75	$t=$	0.19	0.71	1.82	2.5	2.9	3.2		∞
Air: Needles......		$d=$	0.52	1.05	2.06	3.22		4.5		9.8
Spheres......			0.11	0.30	0.69	1.19	1.40	1.70		2.86
Oil: Needles......				0	0.049	0.235		0.54		
Spheres......				0.037	0.083	0.107		0.144		0.48
	90	$t=$	0.16	0.59	1.52	2.1	2.4	2.6		∞
Air: Needles......		$d=$	0.525	1.06	2.13	3.45	4.05	5.02		13.0
Spheres......			0.11	0.31	0.715	1.29	1.50	1.87		
Oil: Needles......				0	0.055	0.28		0.64		
Spheres......				0.037	0.088	0.114		0.157		
	105	$t=$	0.14	0.51	1.30	1.8	2.1	2.3		∞
Air: Needles......		$d=$	0.53	1.07	2.19	3.60	4.46	5.39		16.3
Spheres......			0.11	0.32	0.73	1.35	1.56	1.94		
Oil: Needles......				0	0.061	0.30		0.71		
Spheres......				0.037	0.092	0.120		0.163		

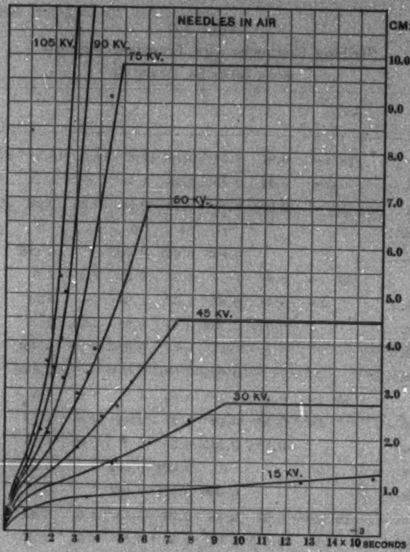
NEEDLES IN AIR
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV.
CM:
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14 × 10⁻³ SECONDS

FIG. 13

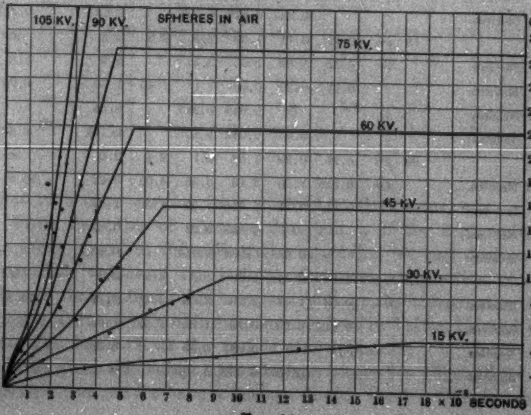
SPHERES IN AIR
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV.
CM.
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18 × 10⁻³ SECONDS

FIG. 14

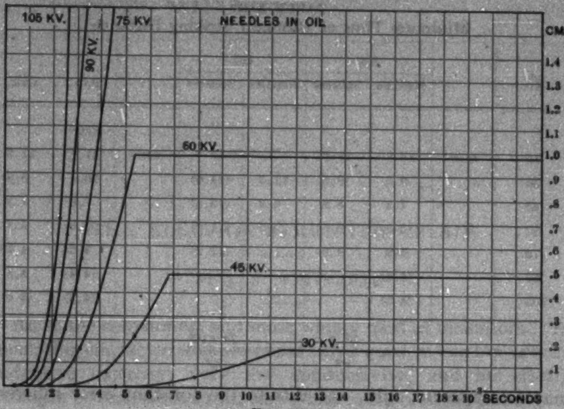
105 KV.
90 KV.
75 KV.
NEEDLES IN OIL
60 KV.
45 KV.
30 KV.
CM.
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18 x 10
SECONDS

FIG. 15

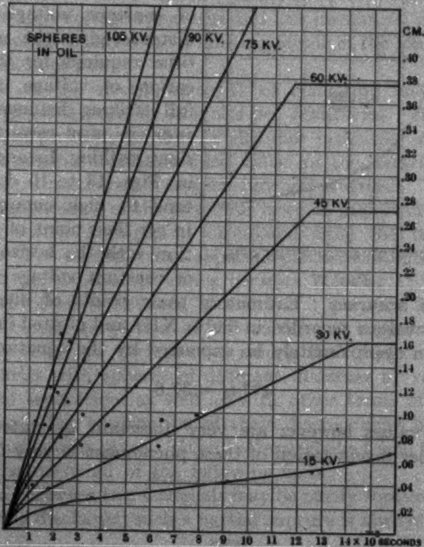
SPHERES IN OIL
105 KV.
90 KV.
75 KV.
60 KV.
45 KV.
30 KV.
15 KV.
CM.
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
1
2
3
4
5
6
7
8
9
10
11
12
13
14 x 10
SECONDS

FIG. 16

TABLE XIII
Minimum Time of Standard Striking Distance

e Kv.		Air		Oil				
		Needles	Spheres	Needles	Spheres		Avg.	Calc.
							$\times 10^{-3}$	
15	$t_0 =$	16.8	17.5		17	$\times 10^{-3}$	17.1	17.2
30		9.5	9.5	11.3	(14.4)		10.1	9.9
45		7.4	6.8	6.9	(12.4)		7.0	7.2
60		5.9	5.5	5.3	(11.7)		5.6	5.7
75		4.9	4.8		(11.2)		4.85	4.75
90		(4.4)					(4.4)	4.1
105		(4.2)					(4.2)	3.6

$$t_0 = \frac{37.8}{e^{.8}}; \quad (e^{8} t_0)^{3} = \frac{74 \times 10^{6}}{t_0^{3}}$$

may be apparent only, and due to the constant error inherent in the method of test. Producing these twisted curves, until they strike the horizontal line of constant voltage striking distance, gives the minimum time required for the application of voltage, to reach full striking distance. However, in most cases the transient striking distance curves in Figs. 13 to 16 do not extend to high enough values to get their point of intersection with the horizontal line of constant voltage with any degree of accuracy. Estimating these points of intersection, gives the values recorded in Table XIII and plotted in Fig. 17, which can approximately be expressed by the equation:

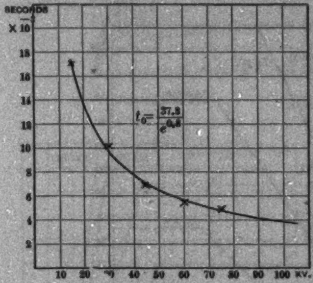

FIG. 17

$$e^{0.8}\, t_0 = 37.8$$

These values however are very uncertain, as stated above, and further investigation of these phenomena is very desirable.

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THE ELECTRIC STRENGTH OF AIR

BY J. B. WHITEHEAD

Air is the commonest and most widely used of insulators. Its insulating characteristics are remarkably good; it has low specific inductive capacity, very low conductivity, and an electric strength or resistance to rupture which until recently has met all the demands of the electrical engineer. As a result of the increase in values of transmission voltage, however, and of improvements in high-voltage apparatus and line insulators, the electric strength of air has become a limiting factor in the long distance transmission of power.

Values of the electric strength of insulating materials are usually given in volts or kilovolts per centimeter. In the case of air, and probably in that of all other insulating substances, it is not possible to state a fixed value for the electric strength for standard conditions of temperature and pressure. The shape, size and separation of the terminals have an important influence on the electric strength as calculated from the break-down voltage. For example, the apparent electric strength of air in kilovolts per centimeter varies between 5.5 and 12 for needle points at distances between 75 cm. and 1 cm., and approaches 100 for corona formation at the surface of very small wires. Similarly there are discrepancies among the values derived from experiments with spheres of different diameter at various distances of separation, as well as with other forms of discharge terminals. The explanation of these discrepancies has not yet been satisfactorily given. It will ultimately be found however to involve some or all of the following facts:

The air between two terminals may be partly ruptured without a resulting discharge; such a partial rupture is always a cause of copious ionization; this ionization is a separation of the ultimate particles of the air into positive and negative charges or gaseous ions which render the air highly conducting. Besides these there is a further peculiarity of the structure of the air in the neighborhood of conductors which results in a marked and regular dependence of the electric intensity causing ionization, on the radius of curvature of the electrode; this fact is particularly interesting in that the phenomenon occurs under a variation of dimensions 10^6 times as great as the mean free paths of the molecule and free electron in the atmosphere, and is thus apparently not directly connected with these quantities.

An example of the influence of these facts is the spark between needle points. The high value of potential gradient at the points causes break-down in their neighborhood, resulting in ionization, conductivity, and consequent change of shape of the effective terminal from a point to a sphere or other solid shape. The sphere enlarges until the intensity at or near its surface, decreasing with increasing radius, falls to a value which cannot further ionize the air, and there is then equilibrium without discharge. For spheres of a certain size and range of separation ionization is followed by an increase in electric intensity, and in this case is immediately followed by disruptive discharge.

Alexander Russell,* in a most valuable paper, has considered various types and sizes of terminal in which there can be no initial ionization without resulting discharge. He shows from the results of various investigators that if the terminals are chosen for these conditions, a constant value of about 39 kilovolts per centimeter is found for the electric strength of air. He also draws some interesting comparisons between his own results with spheres and those of Steinmetz with needle points, showing that they are in fair agreement when the facts of ionization as above described are considered. Russell's conclusions lead to very uniform results for the particular cases he examines, and by an extension of his reasoning it would appear that if we could determine the voltage of initial ionization or break-down for a given pair of terminals, and could calculate the corresponding potential gradient, we should arrive at the same value of the electric strength of air for all shapes and sizes of terminals. This is not the case however.

As is well known, the surface electric intensity at which cylindrical wires begin to discharge increases markedly with decreasing diameter of wires. For wires of diameter one cm. and larger, the critical surface intensity is constant at about 40 kilovolts per cm., and this corresponds to the value found by Russell, and also to the value at which secondary ionization sets in, as determined by Thomson and others working with vacuum tubes. For wires smaller than one cm. the critical intensity increases, reaching the value 80 for a diameter 0.1 cm. The ionization theory offers no obvious explanation at this point, nor does Russell discuss the fact that the surface electric intensity for wires smaller than one cm. diameter may be raised far above 39 kilovolts per cm. without any evidence of break-down or ionization of the air. In fact it should be noted that Russell's constant value of 39 kilovolts per cm. depends on the assumption, not yet justified except by his conclusions, of a constant value of "lost volts" at the surface of separation between terminal and air. The apparent variation of the electric strength of air with the diameter of wire is a most promising problem for the experimental physicist. The suggestion by several writers that the air has greater strength near the wire than at a distance is only an unscientific statement of the fact. Undoubtedly the electric strength of the air will ultimately be found to be constant. The influences which for small wires reduce the actual intensity below the apparent value, and make necessary Russell's assumption, will be discovered and the correction factor for any type of terminal will then be available. Some further discussion in this connection will be found at the end of the paper.

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* A bibliography of the principal articles referred to is given at the end of the paper.

The apparent values of critical surface intensity for cylindrical wires as determined by different observers differ considerably. The principal workers in this field have been Steinmetz, Scott, Ryan, H. B. Smith, Mershon and Watson. With the exception of the last named an account of the work of each has been presented to the Institute. Steinmetz, Ryan and Watson worked within the laboratory; Scott, Smith, Mershon and Watson on aerial lines. Watson worked with continuous potentials only. If all the observations be expressed in terms of critical surface intensity there is a marked difference in the results. Omitting those of Mershon the others show differences as great as 10 per cent for wires in the neighborhood of 0.3 cm. diameter, while the results of Mershon fall 33 per cent below the lowest of the others. Ryan and Watson have studied the influence of atmospheric pressure, Ryan that of temperature, and Mershon notes a decided influence of water vapor in the air, Ryan's investigation in this direction being inconclusive. Two general methods of observing the point of initial break-down have been used; the visual appearance of corona, and the break, more or less sharp, in the curve connecting voltage and line current or line power. The first method introduces a considerable possibility of personal error. The second method necessitates the elimination of leakage, charging current, and transformer losses, which are often many times larger than the quantity sought, and its accuracy is open to some question.

PRESENT INVESTIGATION

The primary aims of the present investigation have been the development of an accurate method of determining the electric strength of air in the neighborhood of round wires; the application of the method to clean smooth wires of various materials of diameter less than one cm.; and a study of the influence of moisture on the electric strength of air near smooth and rough wires. In addition, some interesting properties of the visual corona are described.

The Method. The new method developed permits a determination of the critical intensity or electric strength of air in the neighborhood of round wires to an accuracy within 0.5 per cent. It also permits accurate control of the temperature and moisture content of the air under observation. It makes use of the fact that electrical rupture is invariably accompanied by ionization, and that extremely minute traces of ionization may be detected by the gold leaf electroscope, one of the most sensitive instruments at our disposal.

The wire is stretched along the axis of an outer metallic cylinder, and the voltage applied between them. Air is drawn from the neighborhood of the wire under investigation and over a suitable discharge terminal connected to the gold leaf system of the electroscope G, Fig. 1. As soon as the ionization accompanying electrical break down occurs the electroscope discharges.

Near each end of the outer cylinder a series of small holes is drilled permitting air to be drawn through the cylinder. The electroscope terminal is placed close to the openings by which the air leaves. The electroscope retains its charge until the critical voltage is reached and then discharges rapidly. A diagram of the apparatus and auxiliaries is shown in Fig. 1. A is the wire accurately centered in the outer cylinder; it is supported under tension by dry threads well beyond the ends of the cylinder which are closed by the wood and glass caps *B B*. Air is drawn through the cylinder by an exhaust fan, entering at *C* and leaving at *D*; the velocity of the air is measured at *F*. Any degree of moisture is obtained by bubbling the air through water at various temperatures, and the driest state by drawing through a large column of calcium chloride. The temperature of the air was controlled by passing it through a large coil of lead pipe immersed in a tank filled with ice or water of any desired temperature. The moisture content of the air was determined by reading its temperature and also the temperature of the dew point, as indicated by a polished brass mirror at *E*; water of any temperature could be passed through the solid back of this mirror, the temperature being read from a thermometer with its bulb immersed in mercury. The temperature of the air was read at each end of the tube, and by means of the coil described was varied between 6 and 40 deg. cent. The dew point could in this way be read to 0.5 deg. cent. and values of relative humidity from 0.1 up to saturation were obtained by the methods described.

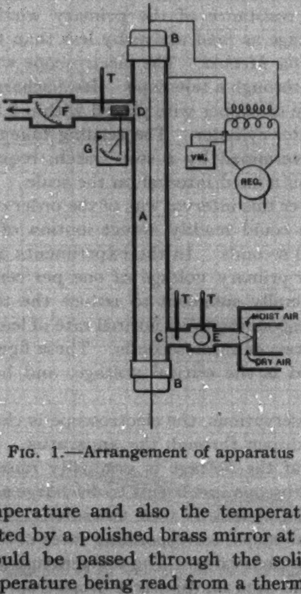

FIG. 1.—Arrangement of apparatus

The voltage was obtained from a 3-kw., 60-cycle transformer, 100 to 25,000 volts, the high tension winding being in four sections. The primary voltage was read on a Weston dynamometer voltmeter, standardized for this work, and was controlled by an induction regulator; for close adjustments a small amount of resistance, of negligible influence on the wave form, was inserted. The ratio of turns of the transformer as obtained from the manufacturer is 1 to 250.18 and this value is used for determining the secondary voltage. The charging current of the wire and cylinders is negligible, and no evidence of leakage current could be detected on an ammeter in the high-voltage circuit, reading to less than one tenth the normal full-load transformer current. The resistance of the primary winding affected the secondary voltage as read above by less than 0.1 per cent.

Accuracy of the Method. The electroscope was provided with a scale viewed through a telescope. Its discharge terminal was a cylindrical cage of copper wire placed within 0.5 cm. of the wall of the main outer cylinder. The reading taken was the time in seconds, as determined by a stop-watch, required for the gold leaf to pass over a fixed interval on the scale. The normal time for free leak over this interval was of the order of magnitude of a day. The eye could readily detect motion of the leaf corresponding to 250 seconds. In the experiments on clean wires an increase in the primary voltage of one per cent at the critical value was generally sufficient to reduce the time of discharge from that corresponding to its normal rate of leak, *i.e.*, thousands of seconds, to two or three seconds. These figures indicate how sharply marked is the critical voltage, and how sensitive the electroscope.

In taking observations, the electroscope is charged and a slow current of air drawn through the apparatus. With eye on the electroscope leaf the voltage is gradually raised to a value at which the electroscope just begins to discharge as detected by the eye, and its rate of leak is then measured. The voltage is increased by small steps, corresponding rates of leak being taken several times for each value. The temperature and pressure were also noted. The time for discharge drops from practically an infinite value to very low values (from two to four seconds) within a very small change of voltage. Several of the many sets of observations are given in Table III and elsewhere, and reference is made to curve 2 in Fig. 7 for the sharpness with which break-down begins. The curves are plotted between time to discharge as ordinates, and kilovolts as abscissæ.

TESTS AND EXPERIMENTS

The first experiments described are an investigation of the influence of the velocity of the air through the apparatus. The corrections for temperature and pressure variation are then discussed. Then follow the observations on wires of various sizes, and materials under various conditions as to surface and moisture.

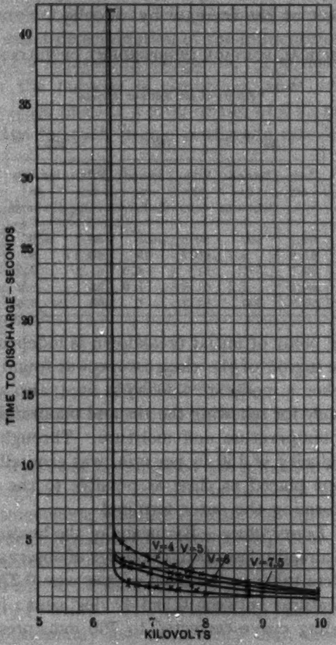

FIG. 2.—Influence of air velocity on rate of discharge

Effect of Air Velocity. A series of observations is given in Table I showing that the method as described is, within wide limits, independent of the velocity with which the air is drawn through the apparatus. A series of curves plotted from another set of observations is shown in Fig. 2. The point of initial break-down is not affected by the velocity, but the rate at which ions reach the electroscope is. In the observations from which the curves are plotted, the electroscope was some distance from the discharging wire, permitting diffusion and recombination of the ions. The curves from the values in Table I are all superposed, since in this case the electroscope was very close to the discharging wire, and even at no motion of air in the tube the diffusion or projection of the ions from the discharging wire is of sufficient volume to discharge the electroscope so rapidly as to mask any effect of the increase by velocity.

TABLE I. CRITICAL VOLTAGE INDEPENDENT OF VELOCITY OF AIR

Velocity of air, feet per minute									
0		98		162		252		371	
Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge	Primary volts	Seconds to discharge
60.5	300	60.5	400	60.5	425	60.2	400	60.7	500
61	5	61.6	2.7	60.7	18	60.8	9	61.2	3
61.8	2.8	62.5	1	61	4.5	61.2	2.2	62	1
62.1	2	61.2	2.2	61.5	1.8	62	1.2	—	—
63.5	0.8	60.6	300	62.5	1	63	0.6	—	—

As seen, the point of initial breakdown is independent of the velocity. The action of the electroscope was found to be more pronounced when a moderate velocity is used; also a continuous draft is necessary for renewing the air, and maintaining constant conditions of temperature and moisture. Throughout the experiments a velocity of 150 ft. per min. was generally used, and the electroscope placed as close as possible to the outlet from the cylinder forming the outer terminal.

Influence of Temperature.—By means of the heating and cooling apparatus already described, the series of observations, given in Table II, were taken on polished copper wire 0.276 cm. diameter at temperatures between 6 and 41 deg. cent., Fig. 3 shows the corresponding curve corrected to 760 mm. pressure.

TABLE II. INFLUENCE OF TEMPERATURE ON CRITICAL VOLTAGE

Mean temperature, cent....	7.4	11.0	16.4	20.0	20.5	27.9	41.0
Primary volts observed....	71.6	70.7	70.5	69.1	70.2	69.0	66.8
Barometric pressure.......	763.0	755.8	764.0	755.8	765.5	765.5	765.5
Primary volts corrected to 760 mm................	71.4	71.0	70.1	69.5	69.8	68.4	66.3

In these experiments the temperature of the air was read at the points of entering and leaving, the cylinder being covered with heat-insulating materials so as to maintain the temperature as constant as possible. The difference in temperature between the entering and leaving air was a maximum at four degrees at the highest temperature, and the mean values are given in the table. This test was undertaken to ascertain the correction factor for temperature to be applied in the later investigations. The results are not offered as being the most accurate attainable, and a more exact determination of the influence of temperature is planned for a separate investigation. The results are amply accurate for the purpose of correction, and indicate that at 760 mm. pressure there is a drop or rise of 0.22 per cent in the critical voltage for each degree centigrade rise or fall from 21 deg. cent. Ryan has investigated the influence of temperature on the voltage at which the corona becomes visible, and his results at atmospheric pressure indicate the value 0.27 per cent per centigrade degree above or below 21 deg. cent. In the present experiments, critical voltages are reduced to 21 deg. cent. by means of the factor 0.22 per cent per degree.

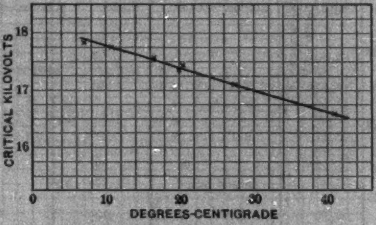

FIG. 3.—Influence of temperature –0.276 cm. wire in 6.35-cm. tube

Influence of Pressure. The variations in atmospheric pressure introduce considerably less disturbance than those of temperature. The minimum and maximum pressures encountered in these experiments were 750 mm. and 772 mm. Ryan and Watson have investigated the influence of pressure, but their results are not in good agreement. In these experiments, critical voltages are reduced to 760 mm. pressure by Ryan's factor. The values of this factor vary from 0.985 for 750 mm. to 1.009 at 766 mm. My observations within the narrow range stated above are in fair agreement with these values, being 1.88 per cent variation, as against 1.53 per cent by use of Ryan's expression. As most of the observations were taken at pressures differing little from 760 mm., and necessitating corrections of only a few tenths of a per cent, no separate investigation of pressure influence was undertaken.

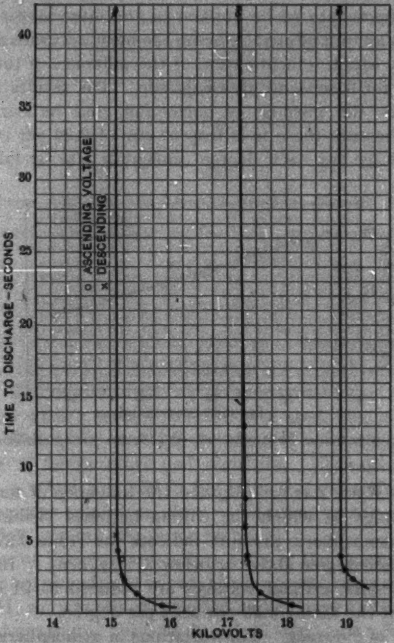

Fig. 4.—Typical curves showing critical voltage for wires of 0.205, 0.276 and 0.347 cm. diameter in 6.35-cm. tube

Observations on Clean Solid Wires

A great many observations were made on copper, aluminum and steel wires of diameters between 0.089 cm. and 0.5 cm. centered in tubes of 4.9 cm., 6.35 cm. and 9.82 cm. internal diameter, and 100 cm. length. The steel wires were taken from rods of tool steel; they were perfectly straight and readily polished and handled without danger of kinks. The copper and aluminum wires were heated by electric current to dull red and at the same time subjected to tension; they were then carefully polished and placed in the outer tube without bending or contact with other objects. The two larger tubes were placed in the vertical position and the wire held under tension in accurately centered insulating bushings on the ends. The air was strained through cotton wool and a cambric screen at the entrance to the tube. On raising the voltage the charged electroscope is unaffected until the critical voltage is reached when a sharply marked rapid rate of leak sets in. In Table III several sets of observations on wires of 0.205 cm. and 0.276 cm. are given; Fig. 4 gives two curves plotted from the figures of the table as well as the curve for 0.347 cm. wire. From these it may be seen that at the critical point an increase of one per cent in the voltage is sufficient to cause the electroscope to discharge in three or four seconds although it was unaffected at the lower value. With increasing values of voltage, the electroscope discharges still more rapidly, although owing to its sensibility a point is soon reached when the discharge is so rapid that its time cannot be read. The visible corona ap-

TABLE III. POLISHED COPPER WIRES IN 6.35-CM. BRASS OUTER TUBE

0.205 cm. diam.		0.276 cm. diam.		0.276 cm. diam.	
Primary volts	Time to discharge seconds	Primary volts	Time to discharge seconds	Primary volts	Time to discharge seconds
60	∞	69	∞	68.5	∞
60.3-5	just begins	69.5-6	25	68.8	just begins
60.6	4.2	70.3	2.4 3.4 2.8 2.4	69.3	3.8 4.2
60.8	3.8 3.8 3.6	71	1.6 1.6 1.4	69.2	8 1.3 8
60.9	2.2 2.2 2.2	73.2	0.8	70	1.4 1.4 1.4 1.4
61.8	1.4 1.4	71	1.4 1.4 1.4	72.2	0.6 0.6
62.5	1 1 1	69.7-8	9.2 10	69.3	3.8
63.5	0.6	69	∞	69.2	6
61	2.2 2.4	69.2	just begins	68.7	∞
60.5	5.4	0		0	
60.2	∞	69		68.5	∞
60.3	just begins	69.6-8	9.2	68.9	just begins
				69.2	7 6
		70.3	2 2	70.1	1.4 1.4
Temperature 19 deg. cent. Barometer 764 mm. Dew point 5 deg. cent. March 4		Temperature 19.5 deg. Barometer 761 mm. Dew point 4 deg. Feb. 15 Corrected critical volts 68.8		Temperature 21 deg. Barometer 762 mm. Dew point −2.5 deg. Feb. 18 Corrected critical volts 68.7	

pears faintly at the beginning of the break in the curve and brightens rapidly with increasing voltage. Recalling Ryan's observations that corona and power loss begin together, this shows that there is no ionization before power loss sets in. The nature of the power loss has been the subject of much speculation, and the above fact is one leading to my conclusion that a part if not all of the loss is in the process of ionization, *i e.*, the separation of the two opposite charges on the molecules of the gas. The shape of the curve beyond the critical point depends on the air velocity, distance to the electroscope, size of its terminal etc., and it offers a means of studying the shape of the loss curve for voltage above the critical value. The investigation has not as yet been extended in this direction.

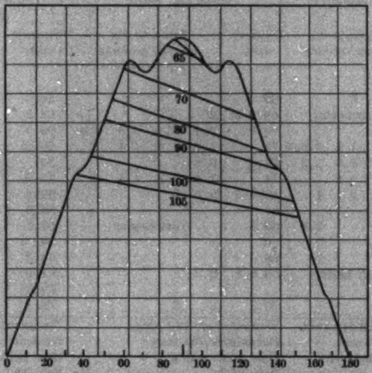

FIG. 5.—Region on voltage wave occupied by corona at various voltages

A further fact of interest in connection with these curves is that for decreasing voltage the curve is retraced, and ionization or break-down ceases at the same voltage at which it began. There is thus no apparent after-effect of foregoing ionization. This fact may be also observed by opening the transformer circuit when the electroscope is discharging; it stops instantaneously even when its initial rate is extremely rapid, *i e.*, when ionization is copious. This indicates that the life of a free ion is extremely short, and also in view of the low air velocities used that the ions reach the electroscope by their own velocity in the electric field, rather than by any aid of the air draft. This conclusion is in accord with the independence of critical voltage and air velocity. Some further evidence in this direction is given in the description of experiments with the corona.

Table III indicates the nature of the observations taken on many variations of size and material of wire and outer tube, under various atmospheric conditions. The results on a given size of wire at different times and in different tubes are in excellent agreement when the corrections for temperature and pressure are applied. This is indicated in Table III and also in Table IV in which the results of tnis portion of the work are condensed. In Table IV the observed values of critical primary volts have been corrected to 21 deg. cent. and 760 mm. pressure by the factors already described. The critical value is that at which the discharge of the electroscope begins. This point is very sharply marked, and under steady circuit conditions could be read to 0.2 primary volts. On the curves of Fig. 4 it corresponds to the beginning of the steep descent of the vertical limb. The maximum electric intensity at the surface of the wire corresponding to the critical primary voltage is calculated from the primary reading by the expression

$$\frac{dV}{dx} = \frac{V}{x \log \frac{b}{a}}$$

in which V is the maximum value of potential difference between wire of radius a, and tube of inner radius b; x is the distance from the center of the wire to the point for which the calculation of intensity is made, and thus for the surface of the wire $x = a$. To obtain V, the primary voltage is multiplied by the ratio of transformation, and the ratio of maximum to effective value of e.m.f. of the 60-cycle circuit used throughout the experiments. An oscillogram of this electromotive force wave was taken, and from careful measurements of the ordinates Fig. 5 is a good reproduction. By the summation of the squares or ordinates sufficiently close together to take account of the irregularities, the ratio of maximum to effective value was found to be 1.45 for one-half wave and 1.455 for a whole wave; the value 1.452 has been used in calculating the values in the last column of Table IV.

In Fig. 6 the results given in Table IV are plotted between diameter of wire and maximum critical surface intensity. With the exception of two points, at diameters 0.276 and 0.325 cm., the curve is fairly smooth. The former point is off only 0.8 per cent and the latter for an aluminum wire about one per cent. Aluminum is very difficult to polish, the finest abrasives leaving streaks and a dull surface; this is sufficient to cause the observed lowering of critical voltage.

TABLE IV. RELATION BETWEEN DIAMETER AND CRITICAL SURFACE INTENSITY

Diam. cm.	Material of wire	Diam. of tube cm.	Material of tube	Critical primary volts corrected	Ratio	Maximum critical surface intensity
0.089	Copper	4.9	Brass	74.5	125.09	77,100
0.122	"	"	"	44.0	250.18	70,950
"	"	"	"	87.8	125.09	70,800
0.156	"	"	"	97.0	"	65,880
"	"	"	"	97.0	"	65,880
0.205	"	"	"	109.5	"	61,350
"	"	"	"	55.0	250.18	61,500
"	"	6.35	"	60.5	"	62,080
"	"	"	"	60.2	"	61,780
"	"	"	"	(8) 59.9	"	61,680
0.254	Aluminum	"	"	65.9	"	58,750
0.276	Copper	"	"	68.9	"	58,080
"	"	"	"	68.8	"	
"	"	"	"	68.5	"	
"	"	"	"	69.0	"	
"	"	"	"	(8) 68.9	"	58,080
"	"	9.52	Steel	77.3	"	57,650
0.325	Aluminum	6.35	Brass	72.8	"	55,000
0.347	Copper	6.35	"	75.13	"	54,500
0.3405	"	9.52	Steel	85.7	"	55,100
0.399	Steel	"	"	92.5	"	53,050
0.475	"	"	"	100.6	"	51,400

This curve is of interest when compared with that of Watson for continuous potentials; the curves coincide for the smallest diameters, but Watson's is lower by 6 per cent at 4 mm. If, as he states, the temperature was constant at 17 deg. cent in Watson's experiments, this suggests that a higher value of alternating potential is necessary for break-down, and that a time element is involved; an elevation of temperature however would account for a part of this difference. Ryan's values at which the corona appears are also plotted for comparison. In the present work frequent observations of corona were made, and its appearance invariably coincided very closely with the critical voltage as indicated by the electroscope read by an independent observer.

OBSERVATIONS ON DIRTY WIRE

Throughout the experiments on clean wires it was found that the least dust, dirt, or other inequality of surface was accompanied by a lowering of the critical voltage. On viewing such a wire through the end of the tube a discharging point could usually be detected. On raising the voltage, other points appear on a dirty wire, and the amount of lowering of critical voltage depends on the size and number of surface irregularities and their location with reference to the electroscope. Thus for copper wire 0.122 cm. in diameter taken from a fairly clean coil and not polished, the drop in critical voltage below that for clean wire was only one per cent. On the other hand, a 0.277-cm. polished copper wire, giving a critical surface intensity of 56,500 volts per

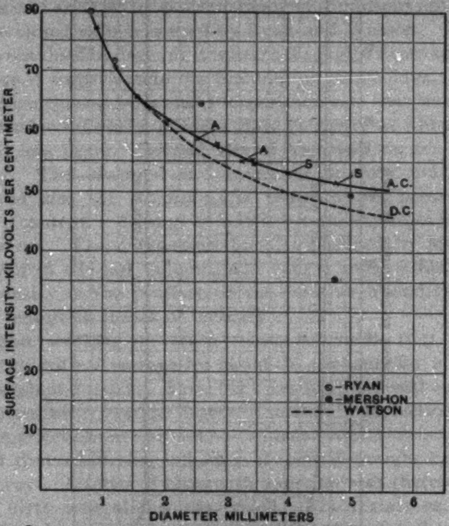

FIG. 6.—Relation of critical intensity and diameter

cm., was heated by current until it took on a flaky coat of oxide. Its critical intensity was reduced to 37,850, or by 33 per cent. Repeated observations (see Table VI) show this point to be very constant and sharply marked. On comparing the discharge curves for clean and dirty wires (see Fig. 7), however, it will be seen that the break in the curve is less sharply marked for the dirty wire and the bend more gradual. This indicates a lesser supply of ions, but a supply amply sufficient to cause a rapid discharge of the sensitive electroscope. It is thus apparent that the figure 37,850 has no significance, only representing the value at which the first surface irregularities begin to dis-

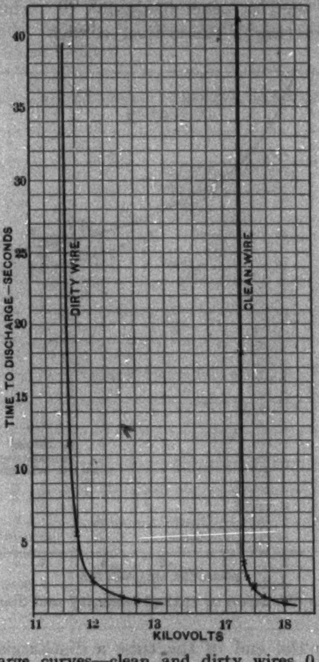

FIG. 7.—Discharge curves—clean and dirty wires 0.276-cm. wires in 6.35-cm. tube

charge. These discharges represent energy loss, and in sufficient quantity may cause the voltage at which appreciable loss begins, to fall far below the value for clean wires.

INFLUENCE OF MOISTURE

The method of securing any degree of moisture content of the air has been described. The continuous draft of air through the apparatus, with temperature and moisture instruments close to entrance and exits, ensures a constancy of conditions not possible with the closed cylinders used by Ryan and Watson. Moist air was also obtained by drawing it upward through a dense spray, and by taking it from outside the building on rainy days. The invariable conclusion from many experiments is that moisture in the air has no influence on the surface intensity at which ionization and loss begin. Several sets of observations are given in Table V. The observed and corrected primary voltages are given and also the conditions of temperature, pressure, and moisture content. A range of relative humidity from 0.1 to 0.9 was covered. The " vapor product " as defined by Mershon is also given in the last column, and ranges from 0.008 to 0.83; this quantity is the product of the relative humidity by the vapor pressure in inches of mercury.

Mershon, working on aerial wires, concludes that moisture lowers the critical voltage by about 16 per cent for a range of vapor product 0 to 0.6. Since his wires were exposed to weather they were subject to some degree of surface imperfection. Since such imperfections are an aid to condensation of moisture it was thought that a lowering influence of moisture might be possible in this way. A series of tests with moist air was therefore made on the dirty wire already described. The results as given in Table VI indicate that in the case of dirty wire also, the moisture content of the air has no influence on the value of voltage at which ionization and loss begin. A possible influence of the velocity of the air through the apparatus in checking condensation was also investigated by drawing moist air through for some time, testing for critical voltage, then stopping the air draft and testing, etc. In no case was it possible to detect any influence of the moisture content on the critical voltage.

It is difficult to imagine any other conditions of Mershon's experiments which might explain an influence of moisture. His wires were suspended by paraffined cords over which the loss was only one or two per cent, and consequently all losses save those in the atmosphere itself were practically eliminated. Floating particles and mist depositing on the lines would lower the critical voltage but with given surface conditions, the experiments de-

TABLE V. CRITICAL VOLTAGE—MOISTURE CONTENT—CLEAN WIRES

0.206 cm. diameter						
Primary volts at which discharge begins	Temperature of entering air deg. cent	Temperature of dew point deg. cent	Barometer mm.	Primary volts corrected 21 deg. and 760 mm.	Relative humidity	Vapor product
60.3-5 60.3	20	-4	764.5	59.96	0.194	0.025
60.5	19	5	764	59.93	0.4	0.102
60.2 60.1	21	8	764.5	59.9	0.433	0.136
60 60.1	23	16.5	764	60.07	0.65	0.38
59.9 60	24.8	18	764	60.21	0.68	0.41
59.2	27	23	763.5	59.71	0.82	0.624
59	28	25	763.5	59.62	0.9	0.833
60.5	20	0	763.5	60.07	0.264	0.047
0.276 cm. diameter						
68.8	21	-10	761.5	68.7	0.108	0.008
68.8 68.9	21	-2.5	761.5	68.75	0.208	0.031
68.8 69	20.4	1.5	761.8	68.8	0.293	0.060
68.8	24	8.5	762.8	69.2	0.374	0.122
68.8	25	13	762.8	69.2	0.47	0.204
68.5 68.8	26	16	763	69.1	0.546	0.292
69	21.6	15	763	68.9	0.66	0.33
68-69	23.4	18	763	68.7	0.72	0.43
68.5-69	20	17	760	68.7	0.86	0.504
0.347 cm. diameter						
75.3	19.6	3	760	75.0	0.33	0.072
75.2	19.8	8	760	75.0	0.46	0.147
75.1-75.5	22	12.5	760	75.4	0.54	0.23

scribed above indicate an entire absence of any influence of moisture. Mershon also finds that the rate of loss beyond the critical voltage increases with the vapor product. Here also no obvious explanation offers itself. The curves of the present experiments between discharge rate of electroscope and voltage show that either the number or the velocity of the free ions about the wire is lessened in moist air, and this means a less loss. This result is in conformity with those of many other experiments. It has long been known for instance that the conductivity of air is lessened by moisture; also that the velocity of ions is less in moist air than in dry air. Steinmetz notes an increase of electric strength of air by the presence of fog and steam. Zeleny has shown that between dryness and saturation the voltage of initial discharge between a point and a plane is constant for negative potentials, and varies by less than 1.5 per cent for positive potentials. He also shows that the currents of discharge are both lowered with increasing moisture content.

TABLE VI. CRITICAL VOLTAGE—MOISTURE CONTENT—DIRTY WIRE 0.297 CM. DIAMETER

Primary volts at which discharge begins	Temperature of entering air deg. cent	Temperature of dew point deg. cent	Primary volts corrected 21 deg. and 760 mm.	Relative humidity	Vapor product
46.5 47	19	0.5	46.2 46.7	0.282	0.05
46.5 47	19	6	46.2 46.7	0.428	0.11
46 46.2	20	9	45.8 46	0.49	0.16
46 46.5	21	12.5	45.9 46.4	0.58	0.24
45.5 46	25	18	45.8 46.3	0.65	0.39
45.5	26	19	45.9	0.65	0.41

When the critical voltages observed by Mershon are reduced to electric intensities at the surface of the wires they are found to be well below these of Ryan, Watson, and the values given in this paper. For example, the loss from a 0.472-cm. wire, according to Mershon, begins at a surface intensity 35,000 volts per cm., see Fig. 6; the value found in the present experiments for the same size wire is 51,000. This difference of 30 per cent can only be accounted for in three ways: (1) The method of taking the critical point from the loss curves. (2) Dirt and irregularities on the wires. (3) Break-down of the air near the strings at a lower value than that necessary on a free wire. Examination of the curves show that the critical point is taken close to the sharp upward break of the curves, and the method offer small chances of too low a choice of critical value. Dirt and irregularities will lower the critical voltage, but require extreme conditions for as great a lowering as 40 per cent, as is indicated by the experiments already described. With the larger wires used by Mershon, it does not seem possible that this degree of surface irregularity could result from any deposit from the air. The third possibility mentioned seems to have been eliminated by the tests to which the cords were subjected before using.

In view of these discrepancies, one naturally turns to Mershon's method of measuring the loss as a possible source of error. This method involves the elimination, by means of a differential wattmeter, of transformer losses aggregating several times the value of the loss to be measured. The method is elegant in conception, but in view of the small losses to be measured, it is to be regretted that its accuracy could not be tested further than described. Since Mershon's observations appear to have been taken in all seasons, it may be stated that a range of temperature of 35 deg. cent. and of pressure of 25 mm. of mercury, and an error of 5 per cent in the critical point as taken from the curves, would give a range of critical voltage as wide as that attributed by him to moisture.

Experiments on Coronae

One of the most striking phenomena in the experiments already described is the extreme sharpness with which the critical voltage appears. The sharp stoppage of the electroscope discharge on interrupting the alternating voltage, and the coincidence of discharge curves for ascending and descending voltage, in the present investigation, indicate that any after-effect of the ionization due to corona must be of duration less than one-half a period. Ryan showed in beautiful manner how the appearance of corona was accompanied by a hump on the charging current curve in the neighborhood of the maximum of the voltage wave, thus suggesting a periodic character. In order to investigate these phenomena further the following stroboscopic device was used: A 0.156-cm. polished copper wire was stretched along the axis of an outer cylinder of 10.5 cm. internal diameter, and voltage applied between them. The wire was viewed longitudinally through six slits, each 4.7 mm. wide, in a disk driven by a six-pole synchronous motor; the slits were on a circle of 27 cm. radius. The position of the eye was fixed by an eyepiece on a screen movable about the motor axis; this screen had a small radial slit 0.5 cm. wide, under the eye piece and opposite the circle of slits in the revolving disk. The angular position of this slit was read on a circular scale. The eyepiece therefore moves through 56 cm. in covering the interval corresponding to one period of the alternating circuit. On viewing the corona with this apparatus, it is at once found that there are certain regions where it cannot be seen and others where it is readily visible, thus showing its periodic character. Further the points of separation of dark and bright regions are sharply marked, so that it is possible to determine quite accurately over how great a proportion of a period the corona exists. A set of observations for various voltages, above the critical value, are given in Table VII. The first column gives the voltage on the transformer primary; the second column, the scale reading at which the corona becomes visible advancing the eye piece from the dark region towards the bright, and in a direction contrary to that of the motion of the disk. The observation therefore is of the angular position at which the corona ends. The readings of two independent settings of the eyepiece are given for each voltage to indicate the accuracy. The position corresponding to zero value of electromotive force was obtained by an instantaneous contact device and voltmeter connected across the transformer primary. The third column gives the average readings reduced to electrical

TABLE VII. LOCATION OF CORONA ON VOLTAGE WAVE

	Corona appears			Corona disappears			
Primary volts	Degrees of scale	Electrical degrees		Degrees of scale	Electrical degrees		Starting Intensity
		Reading	Corrected		Reading	Corrected	
105	10.4 10.8	31.8	27.1	50 50	150	143.5	66,500
100	12.5 12.7	37.8	33.1	48 47.2	142.8	136.3	68.300
90	14.6 15.4	45	40.2	45.4 45.4	136.2	129.7	74,200
80	16.6 17.4	51	46.3	43.8 44.2	132	125.5	70,000
70	19 19.2	57.3	52.6	42 42	126	119.5	70,500
65	27.6 27.8	83.1	78.4	34.6 34.2	103.2	96.7	70,600
65	26.5 27	80.2	75.5	33 33.2	99.3	92.8	—

degrees, and the fourth column these values corrected for the width of the slit and referred to the zero value of electromotive force determined as described above. The succeeding columns give the corresponding readings of angular position at which the corona can no longer be seen. This observation is therefore the angular position at which corona begins on the rising side of the electromotive force wave.

The results in Table VII indicate that the corona corresponding to a given voltage will persist on the decreasing side of the wave to a value below that at which it starts on the side of rising voltage. After the intensity drops below the value at which ionization begins the foregoing plentiful ionization is able to preserve luminosity for an appreciable interval. This interval is seen to be extremely short and of the order of magnitude of one or two thousandths of a second. In fact the settings for vanishing point of corona on the side of decreasing voltage are somewhat less sharply marked indicating that the corona fades off more gradually than it starts. The readings for 65 volts primary taken on different days show some discrepancy. The corona is very faint at this voltage close to the peak of the electromotive force wave and therefore very sensitive to reading error and voltage variation. In this region, also, the accuracy of setting is somewhat impaired by the presence of the three peaks of the electromotive force wave.

The wave form as measured from the oscillogram is plotted in Fig. 5, and the ordinates at which the corona starts and ceases for the several values of primary voltage are indicated; the voltage is rising on the left side of the curve. The ordinates corresponding to the angles given in Table VII indicate voltage values which by obvious calculation permit the evaluation of the figures for surface intensity at which the coronæ begin. These values are given in the last column of Table VII. They are in fairly good agreement, considering the method by which they are obtained with the accurate figure for this wire 65,800 as determined with the electroscope. It is altogether probable that this latter figure is the real value at which the corona starts on the rising side of the wave, and if it be taken as a basis the lag of the point at which corona vanishes would be somewhat lessened from the values indicated in Fig. 5.

Positive and Negative Coronæ. The arrangement of apparatus as described above superimposes the coronæ corresponding to the positive and negative halves of the electromotive force cycle.

By closing alternate slits in the revolving disk it is possible to view the positive and negative coronæ independently. Several sets of readings were made for each half wave of the angle at which corona begins and ends. The readings for the two half waves were made on the same portion of the scale by reversing the field of the synchronous motor. The points of beginning and ending of corona were found to be independent of the polarity of the wire. There was very little difference to be detected in the appearance of the two coronæ; if there is any difference it is a somewhat greater brightness and sharper definition of one.

The extreme sharpness with which the corona appears was well illustrated in the stroboscopic experiment in various ways. For example, when viewing the corona near the position at which it is cut out, very small voltage fluctuations are reflected as flickers in the corona. By setting the eyepiece very near to the position of eclipse, a regular pulsation of the corona was generally visible, and was traced to a slight hunting of the motor, thus causing a vibration of the eclipsing edge of the hole in the disk about its true synchronous position. A further evidence of sensibility could be seen by adjusting the voltage so that the critical value was in the region of the three peaks on the crest of the wave, as shown in Fig. 5. It was then possible by moving the eyepiece to pick out the several peaks separated by the dark intervals corresponding to the depressions.

Diameter of Corona. It has been suggested by Steinmetz and others that the diameter of the corona is such as to reduce the electric intensity at its boundary to the constant value of the electric strength of air, *i.e.*, about 40 kilovolts per cm. Jona states that the diameter of the corona for a given arrangement of conductors is independent of the size of the wire and depends only on the voltage. Also that the diameter is such as to reduce the electric gradient at its boundary below the electric strength of air. The same suggestion has been made by Russell in several places.

The measurement of the diameter of the corona is very difficult. Jona's figures and conclusions are apparently based solely on eye estimates of the diameter. Photographic methods fail, since the phenomenon is accompanied by much invisible ultraviolet radiation. A preliminary attempt looking to the development of a method for measuring the diameter of the visible corona is described below; it has yielded results which are sufficiently concordant to make them worthy of recording here. The experiments are being carried further in this most interesting direction.

A slit was cut in the wall of the outer 15.2-cm. cylinder and at right angles to the axis. A 0.156-cm. wire stretched along the axis develops a well defined corona for voltages above 18,000. A screen one cm. wide was placed transversely across the slit and close to the wall of the outer cylinder. The screen was moved up and down to positions in which its upper and lower edges cut off the corresponding edges of the corona, the eye being at a pin hole at the horizontal level of the wire and at a distance from the wire 6.15 times that of the screen from the wire. It is necessary in these experiments that the eye be thoroughly rested and accustomed to the darkness. In making the final setting of the point at which the screen completely obscures the corona edge, direct scrutiny is not possible owing to the blind property of the fovea of the eye, and use must be made of the adjacent regions of the retina. In this way any number of quite consistent readings may be taken. The screen was carried on a cathetometer which could be read to a hundredth of a millimeter. The results at effective voltages 28,000 and 24,000 are given in Table VIII. They show that the maximum deviations from the average values of observed diameter are of the order 10 per cent to 15 per cent. This must be regarded as fair, in view of the small diameters measured, and offers good promise for further investigation in this direction.

TABLE VIII. DIAMETER OF CORONA, 0.156 CM WIRE IN 15.2-cm CYLINDER

28,000 volts				24,000 volts			
Top	Bottom	Difference	Diameter corrected	Top	Bottom	Difference	Diameter corrected
11.065	10.45	0.615	0.462	10.335	11.065	0.73	0.324
11.03	10.43	0.60	0.48	10.375	11.035	0.66	0.408
11.02	10.41	0.61	0.468	10.335	11.06	0.725	0.33
11	10.41	0.59	0.492	10.355	11.06	0.705	0.354
11	10.41	0.59	0.492	10.375	11.06	0.685	0.379
11.035	10.375	0.66	0.408				
Average diameter.......			0.468	Average diameter.....			0.36

As corrected for the width of the screen and the angle at the eye, the diameters of the coronæ at 28,000 and 24,000 volts are

0.46 cm. and 0.36 cm. respectively. The values of electric intensity at the edge of the coronæ, calculated on the assumption that the conductor is enlarged to these diameters, *i.e.*, that the corona has no resistance, are 50,250 and 51,700 volts per cm. respectively. The values of intensity at which the corona forms on solid wires of diameters 0.46 and 0.36 cm. are 51,500 and 54,000.

While it is hazardous to draw conclusions from work as yet so incomplete the above figures for a solid wire and a corona assumed to be perfectly conducting are in such close agreement as to at least suggest: First, that the edge of the corona marks the limit of ionization or rupture; and second, that the corona has high conductivity, the greater part of the potential difference, and hence loss, occurring beyond its boundary. On this assumption the loss would be due to the forced passage under the electric gradient of molecular ions through the air. It is to be noted however that these figures do not indicate that the intensity at the edge of the corona is 40,000 volts per cm., the suggested constant electric strength of air, but that it is higher and its value related to the corona diameter in the same way that the critical surface intensity for a solid wire is related to the diameter of the wire.

Discussion and Conclusions

It is evident from the facts and experiments which have been described above that the laws under which the corona appears are not yet definitely fixed. There are a good many consistent facts, however, which permit us to speculate as to the nature of the corona. The most conspicuous of these facts is that the break-down of the air which is invariably accompanied by a more or less visible corona is attended by copious ionization. Our present knowledge of ionization of gases reveals three possible sources of ions or charged particles: (*a*) the ions may be drawn from the substance of the wire or terminal itself under the electric intensity; (*b*) the molecule of the gas may be disrupted by a separation of its two component charges by the intensity of electric field in which it finds itself; (*c*) a molecule of a gas may be ionized or separated into its component charges as a result of a collision between itself and another molecule or charged particle.

Regarding the possibility of drawing free charges from the metal of the terminals, we have the experimental evidence that the generation of ions in the neighborhood of wires is independent of the material of the wires and we should expect different figures for different materials if initial ionization started in this way. Further it has been calculated that the electric intensity necessary to draw electrons from metal is of a very much higher value than that at which corona begins. With reference to the second possible source (*b*), it has also been shown that the intensity necessary to separate the component charges of a molecule is higher considerably than the intensity at which corona begins at atmospheric pressure.

There is considerable evidence that the third source of ionization mentioned above, *i.e.*, ionization by collision, or secondary ionization as it is called, is that which leads to the starting of corona. There are always a certain number of free electrons or negative charges and of ions of molecular size present in the air at atmospheric pressure. These free charges have their origin in the frequent collisions between molecules and are extremely few in number. A single charge does not have a long independent existence but when it combines with a molecule of opposite charge its place is taken by other charges, so that the average condition is that of a constant number of free charged particles. These charged particles account for the conductivity of the air which may be observed by sensitive instruments. It is the value of this low conductivity which leads to our knowledge as to the number of free charges present.

Now the electron, or corpuscle, the smallest negative charge of which we have knowledge, requires an intensity in the neighborhood of 170,000 volts per cm. in order to give it a velocity sufficiently great to break up a molecule with which it collides. The corpuscle attached to a molecule, however, has a larger mass and consequently if it can acquire sufficient velocity it can the more readily break up a molecule with which it collides. These are the agents which are active in secondary ionization, which has been investigated by many physicists, notably J. J. Thomson, Townsend and von Schweidler. The values at which this class of ionization sets in as determined by physicists working with continuous potentials and generally in vacuum tubes, is between thirty and forty thousand volts per cm. This figure is in very good accord with the value at which corona sets in for wires above one cm. in diameter. The influence of temperature and pressure is also the same in each class of phenomena. It may be stated then with some positiveness that secondary ionization is the cause of the initial break-down of the air and formation of corona.

It is evident that in the formation of the corona very short time intervals are involved, for it begins in the close neighborhood of the maximum value of the intensity wave, and, within the comparatively narrow limits already investigated, is independent of the frequency. It begins and ends at approximately the same value on the wave of intensity when the maximum intensity is above the critical value. If we try to picture the phenomenon of the starting of break down we may reason somewhat as follows: In an alternating electric field the free ions of molecular size vibrate with increasing amplitude as the voltage arises. The velocity is greatest at the maximum value of voltage if as is probable we presuppose some retarding force. If, however, the ion meets nothing its amplitude will be greatest at the end of a half wave. We may suppose that there are always some ions which collide with molecules when their velocity is a maximum. When with increasing voltage this maximum velocity is sufficient to ionize the molecule with which the ion collides secondary ionization sets in liberating more free ions which themselves become ionizing agents and a cumulative effect sets in at once resulting in a general state of ionization.

The intensity (40,000 volts per cm.) at which secondary ionization sets in around large wires corresponds with the value deduced by Russell for the discharge intensity between terminals of various shapes about which there can be no preceding ionization. In cases where there is antecedent ionization the effective terminal enlarges until the intensity at its surface falls to the ionizing value as is indicated by the experiments on the diameter of the corona described above. The value 38 to 40 kilovolts per cm. satisfies many of the cases of discharge which arise and thus offers itself as the long sought constant value of electric strength of air.

There is one important case, however, which is not yet harmonized with this value, namely the case in which the radius of curvature of the terminal is small, the most conspicuous instance being the range of diameter of round wires of less than one cm. In these cases the apparent intensity at which ionization begins is much higher than 40,000 volts per cm. The value of intensity may be carried to 80,000 for small wires and there is not the slightest trace of ionization. To state that the air has a different strength near the wire than at a distance is only another way of stating the fact and dodges the question. As the diameter is decreased it becomes comparable with the space separation of the free ions. There is considerable evidence that under normal conditions there are about 1000 of these ions per cubic cm. of air. This would give them an average distance of separation of about 1 mm. Thus as the ions vibrate near the wire surface they must be brought much nearer together in the case of a small wire. Hence there will be larger forces of repulsion brought into play retarding or limiting the amplitude of vibration and thus necessitating higher values of intensity to overcome these forces.

These are questions for solution by the experimental physicist but the field is at present practically untouched. The application of alternating electromotive forces to the problems of the ionization of gases has been absolutely neglected. Corona formation and the laws which regulate it are of the first importance for electrical engineers since corona is to be prevented both as a source of loss and an enemy of insulation. The field is replete with fascinating problems. Their solution however involves the use of methods and apparatus generally not familiar to the physicist. Hence it is to be hoped that this most interesting field will be entered more generally by experimental engineers.

The experiments described in this paper were carried out at the Johns Hopkins University. The author wishes to acknowledge the valuable assistance of Dr. C. F. Lorenz and Mr. P. G. Agnew.

SUMMARY OF RESULTS

The conclusions from the experiments of this paper may be briefly summarized as follows:

1. A method is described which permits the determination of the electric strength of air near round wires within 0.5 per cent.
2. Values of the electric strength of air near clean smooth wires of diameters between 0.08 cm. and 0.5 cm. have been determined.
3. Temperature and pressure cause the greatest variations in the electric strength of air near a given wire.
4. At 760 mm. pressure there is a drop or rise of 0.22 per cent in the electric strength of air per centigrade degree rise or fall from 21 deg. cent.
5. Water vapor or moisture has no influence on the electric strength of air. Increasing moisture content probably lessens the loss above the critical voltage.
6. There is no loss through air until the critical voltage accompanied by ionization and corona is reached.

7. The electric strength of air is independent of the material of the wire or terminal.

8. The critical voltage may be markedly lowered by dirt and surface impurities. This lowering may be as great as 33 per cent.

9. The corona is periodic but ceases at a somewhat lower value on the voltage wave than that at which it begins.

10. The corona has high conductivity and most of the loss takes place beyond it.

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DIELECTRIC STRENGTH OF OIL

BY H. W. TOBEY

A large part of the apparatus comprising the equipment of electric power transmitting systems depends, for its safe and successful operation, on oil. This fact continues to grow in importance from year to year as the size of the units in which it is used increases, the operating voltages become higher, and the conditions more severe.

Not only must this material be of such consistency that it will circulate freely and so carry heat from the sources where it is generated to external cooling surfaces, but it must be free from any impurities which would injure the insulation or active material of which the apparatus is built; and above all, it must withstand voltage stresses without interruption, year in and year out. Failure to meet these conditions, sooner or later, means failure of the apparatus with which it is used.

It is the purpose of the present paper to outline some of the more important characteristics of oil which fulfil these conditions with special reference to dielectric strength. These characteristics are exemplified throughout by curves and data which have been collected from the results of extensive tests and investigations carried on during a number of years.

NATURE OF INSULATING OILS

The oils now most commonly used for insulating purposes are obtained from crude petroleum by "fractional" distillation this being entirely distinct from the method known as "cracking" distillation, used for obtaining the greatest yield for burning oils. Fractional distillation is carried on in such a way as to yield a sweet, unburned residual oil, while distillates of higher boiling points, after being subjected to various other manipulations become what may be called insulating oils. The process is carried on in such a manner as to preserve the hydrocarbons in their natural form. It is probable that they are composed chiefly of bodies having the general formula $C_n H_{2n+2}$, though without doubt they contain also bodies made up of $C_n H_{2n}$.

This brief description gives an idea of the method used in obtaining insulating oils, together with their composition. The characteristics, such as flashing and burning points, viscosity, etc., depend, of course, upon the limits worked to during the process of distillation and refining. The following data, however, indicates what may be expected from a medium and from a light grade oil.

	Medium	Light
Flashing temperature	180° to 190° cent	130° to 140° cent
Burning temperature	205 to 215	140 to 150
Cold test	−10 to −15	−15 to −20
Specific gravity at 13.5 deg. cent	0.865 to 0.870	0.845 to 0.850
Viscosity at 40 deg. cent (Saybolt test)	100 to 110 sec.	40 to 50 sec.
Acid, alkali, sulphur, moisture	None	None

When free from moisture both have the same dielectric strength (45,000 to 50,000 volts, sine wave, between ½ in. discs placed 2/10 in. apart.)

The two most noticeable differences are in the fire and viscosity tests. The medium grade has a flashing temperature about 50 deg. above that of the lighter oil and a burning temperature about 60 deg. above. As to viscosity, a given quantity of the medium grade oil requires about two-and-one-half times as long to pass through a given orifice as does the light grade, conditions as to temperature, etc., of course, being the same.

It is usually customary for reasons of design to use the medium grade in apparatus such as self-cooled transformers, for example, in which the temperature of the oil at the top, due to overloads, etc., may reach fairly high values, the lighter grade being employed in apparatus such as water-cooled transformers, for instance, where the temperature may be more readily controlled. By this means the maximum possible temperature of the oil will in either case, be well below the flash and burning points. Under these conditions, too, it would require a long time for any external source of heat, such as a fire in the building, to raise the temperature to a point such that the oil would take fire and burn. Combustion would not be supported until the temperature had been raised above the burning point.

FACTORS WHICH CAUSE VARIATION OF DIELECTRIC STRENGTH

In taking up the question of dielectric strength and the factors which cause it to vary, it will be well, in order to avoid possible confusion, first to mention the considerations upon which all remarks and tests contained in the paper are based.

The voltage under which the oil breaks down, while under electric stress, depends upon the maximum value of the electromotive force, not upon the square-root-of-mean-square value. This is a long established fact. If, however, the shape of the electromotive force wave is not distorted during test, the ratio between maximum and square-root-of-mean-square values remains constant, and the latter may be used as a basis for measurements. This applies to all voltage values mentioned in the paper. The ratio between these two values, however, differs with every wave-shape, therefore, if the voltage is to be determined in the usual way from voltmeter readings, it is absolutely essential to have the shape of the e.m.f. wave well defined in order to correctly interpret the results. Moreover, the shape should remain the same throughout all tests and for all voltages. This condition existed during the tests mentioned in the paper. Square-root-of-mean-square values are recorded throughout.

All tests referred to here, were carried on under as nearly uniform conditions as possible. Sine-wave generators furnished the energy. Voltage variation was obtained by field control, in connection with series multiple windings on the low tension side of the testing transformer. No series resistance was used in the controlling system.

According to the A. I. E. E. standard for determining striking distances in air, a non-inductive resistance of one-half ohm per volt should be placed in series with each terminal of the spark-gap to prevent surges which might occur at the time of breakdown. It was suggested that the same precaution might be advisable in connection with the tests between various shaped terminals in oil. This was therefore carefully tried out with a disk and needle point. These terminals give a straight line curve up to a comparatively high voltage and therefore furnish a ready means of checking. Two sets of readings were taken, with increasing distances and for voltages up to 180,000. In one set, a water resistance adjustable to one-half ohm per volt was placed in series with each terminal, while in the other set, the transformer leads were connected directly to the terminals without intervening resistance. The results were identical. All other tests were therefore made without series resistance.

As far as possible, tests were made of uniform duration, low voltage first being applied and increased gradually until breakdown occurred, this usually requiring from five to twenty-five seconds depending on the magnitude of the voltage. In this way the question of time was largely eliminated, although it is probable that the insulating qualities of oil do not change materially under continued stress. This cannot be said to hold true, though, during short intervals, fractions of a second, for example, for in such cases time has an important bearing on the result.

For the sake of uniformity, the same frequency was used throughout, although it is believed that the variations in breakdown values are comparatively small over the range of present commercial frequencies.

The difficulties in carrying on an investigation of this kind are great, owing to the number of variables which may creep into the work. Even with apparently identical conditions, it is sometimes difficult to duplicate results. An enormous number of tests were therefore necessary in order to obtain reliable figures. Every point used in plotting the curves reproduced in the paper, is the result, not of one test, but of a great many, from which an average was taken.

SHAPE OF TERMINALS

The disruptive strength of oil depends to a large extent on the shape of terminals between which it is tested. For the sake of comparison, assume a uniform grade of oil which is clean and free from moisture. The voltage necessary to break through a given distance between two spheres is less than between two disks. That required to disrupt the oil between needle points is less than between two spheres, etc.

The reason for this is at once apparent from diagrams, Figs. 1 to 5. By referring to these and to the curves, Fig. 6, it will be seen that the shapes of terminals which cause the lowest breakdown values, are those which allow the greatest concentration of electric stress at one or both terminals. In other words, the terminal is surrounded by a zone of oil across which the stress is greater than in the next succeeding zone. The oil in the former is strained beyond its strength and breaks down. As soon as this occurs the stress is transferred to the next zone and this breaks, and so on across the entire gap. In actual practice, of course, these ruptures occur in such rapid succession that they are virtually simultaneous.

When the distribution of flux is perfectly uniform, as for example, between large disks placed near together, the average and maximum densities are the same. This no longer holds where the field is distorted, for in this case the stress across one section of the gap, as already indicated, may be very much greater than across the remainder. The distances between terminals may have been exactly the same, yet the second gap will break down at lower voltage because the oil in one section of it was strained beyond its breakdown point. This condition is illustrated in the diagrams, Fig. 1 to 5, which were drawn by first plotting the

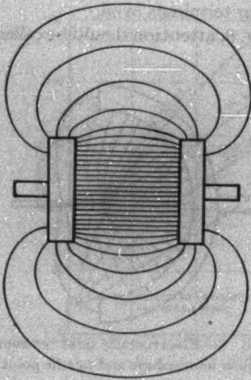

FIG. 1—Electrostatic field between disks

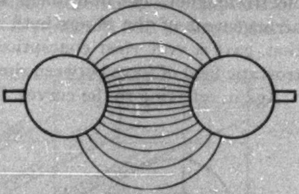

FIG. 2—Electrostatic field between spheres

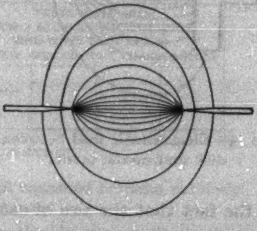

FIG. 3—Electrostatic field between needle points

equipotential lines and afterwards filling in the lines of force, the latter of course being normal to the former at every intersection. The accuracy of the lines was checked in a somewhat novel manner, as follows:

It is well known that the laws governing the distribution of magnetic fields of force are in many respects the same as those governing electrostatic fields. Iron terminals were therefore produced, resembling those shown in Figs, 1 to 5. These were placed, two at a time, on a plane of paper over the poles of an electro-magnet, and iron filings sprinkled onto the paper. The arrangement of the filings both as to direction and concentration, gave a very clear conception of the distribution of an electrostatic field of force between similar terminals in oil.

Again, referring to the curves, Fig. 6, attention should be called

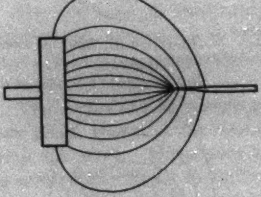

Fig. 4—Electrostatic field between disk and needle points

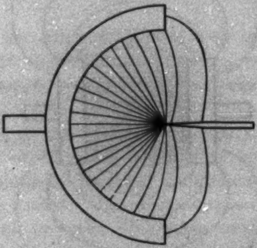

Fig. 5—Electrostatic field between hollow hemisphere and needle points

to the fact that the size of each pair of terminals was the same throughout the range of voltage covered. This means that the distribution of the lines of force in the electrostatic field changed slightly with each setting. In order to determine definitely therefore, the effect of shape of terminal on the breakdown strength of oil for a definite distribution of flux, it would be necessary to use many different sizes so that the dimensions of the terminals would bear a definite relation to the length of gap. The only curve which would not be affected, would be the one referred to needle points. The distribution of the lines of force in this case would be the same for all distances, unless perhaps the rounded shape of the points would have an effect at extremely small distances, small fractions of an inch, for example.

OIL TESTING APPARATUS

The two standards now most commonly used for oil testing are composed of pairs of terminals of definite shape, arranged in a suitable receptacle for holding the oil.

In one of these, the testing terminals consist of ½ in. diameter brass balls fastened to 3/16-in. rods. These are placed vertically in a glass tube and arranged so that they may be adjusted for different distances, 0.15-in. usually being considered standard. Average dry oil should not break down at less than 30,000 volts.*

The other of the two mentioned standards is composed of two ½-in. brass disks, mounted on ⅜-in. rods and arranged horizontally in a receptacle for holding the oil. The disks may be adjusted for different distances although, 2/10-in. has been adopted as standard. Dry oil should not break down in this at less than 45,000 to 50,000 volts, with a sine-wave e.m.f.

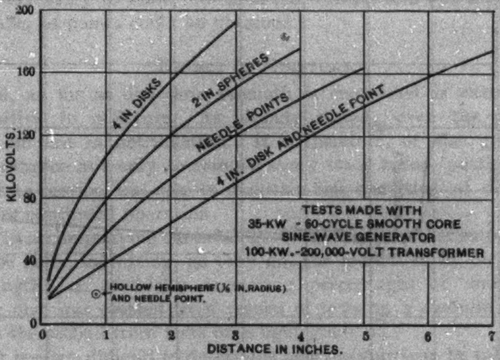

FIG 6—Disruptive voltage of dry oil measured between variously shaped terminals

The disk form of gap was employed in making the various tests mentioned in the paper. It was preferred because of its uniform electrostatic field, and also on account of the fairly large amount of oil which would be subjected to test.

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* Articles by C. E. Skinner, on "Transformer Oil," *Electric Journal*, May, 1904; and by S. M. Kintner on "The Testing of Transformer Oil," *Electric Journal*, October, 1906.

Particles of moisture or other impurities could be detected over a considerable area.

EFFECT OF TEMPERATURE

The dielectric strength of oil does not vary greatly with moderate changes in temperature. One sample tested, for example, stood an average of 52,000 volts at 60 deg. cent. before breaking, and 45,500 or only 10 per cent less, at 20 deg. cent., while at slightly above zero its value had dropped only to 44,000 volts.

Upon congealing, however, as the temperature drops below the freezing point of the oil, the dielectric strength increases with great rapidity, in some cases reaching a value 60 to 80 per cent higher than that just before the freezing point was passed. In the example just referred to, the dielectric strength rose to approximately 77,000 volts, or an increase above 44,000 of 75 per cent.

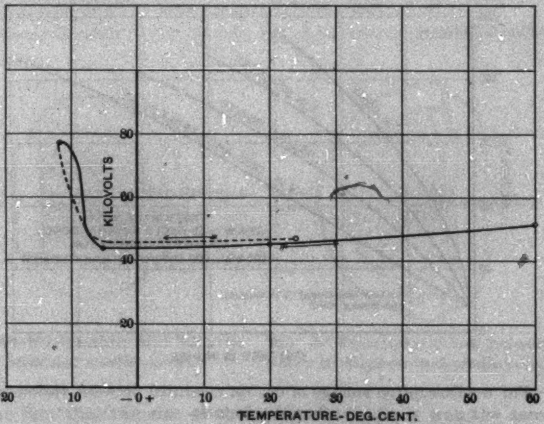

FIG. 7—Effect of temperature on dielectric strength

On heating, the strength drops to the value it had just before freezing, although it is usually necessary to raise the temperature considerably above the freezing point before this occurs. In other words, changes in strength lag behind changes in temperature. Continued heating will finally restore the dielectric strength to its initial value. The accompanying curve, Fig. 7, indicates the cycles through which these changes take place. This may be considered typical for one kind of oil. The values for other kinds are quite likely to vary considerably from those shown by this curve, but the manner in which the changes occur are much the same.

It should be explained that the solid part of the curve was plotted from actual test values, also the beginning and end of the dotted portion. The path followed by the dotted part indicates what may be expected to occur during the first part of the cycle. (As no refrigerating machine was available, it was necessary to make the tests last winter, and but a limited number of points could be obtained.)

EFFECT OF MOISTURE

Oil, as far as dielectric strength is concerned is extremely sensitive to moisture. As already stated, even the slightest amount is detrimental. It is therefore, of the greatest importance not only to remove every trace before putting the oil into service, but also to maintain this condition of dryness under continued operation.

The accompanying curves, Figs. 8 and 9, still further emphasize these facts, indicating, as they do, the reduction in dielectric strength for gradually increasing percentages of moisture. The first was plotted from results of tests on a medium grade and the second from tests on a light grade oil.

It is often difficult to determine how moisture can be taken up by oil contained in apparatus having fairly tight covers, yet this frequently happens, nevertheless. Some of the moisture may settle to the bottom, where it can be gotten rid of by simply drawing off a limited quantity of oil. A certain percentage on the other hand, will be retained and kept in circulation. The percentage which may be safely allowed naturally depends to some extent on the voltage of the apparatus, but that this amount must be extremely small is apparent from the curves just mentioned. Even 3/100 of one per cent, reduces the dielectric strength to three-quarters. (This means but five or six drops of water per quart of oil.) With the addition of 1/100 of one per cent of moisture, the strength is reduced to one-half.

It is evident from the above that the importance of dry oil cannot be over estimated. The apparatus into which it is to be placed, including the interior surface of the tanks, should be thoroughly dried, and not only should the oil be tested for dielectric strength before it is put into service, but at stated periods afterwards, as well. Oil found below the desired value should be dried or replaced with new.

As to the various methods which have been used for detecting moisture, the following may be mentioned:

A quantity of oil may be placed in a tank and allowed to settle for a week or ten days, at the end of which time a sample may be taken from the bottom with a glass tube, or a thief. If much water is present, the eye will readily detect it.

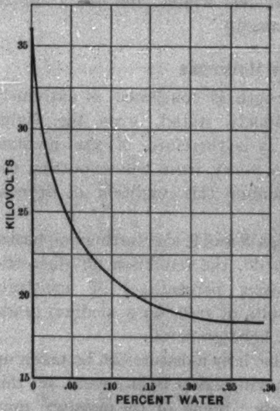

Fig. 8—Influence of moisture on dielectric strength of oil of medium viscosity

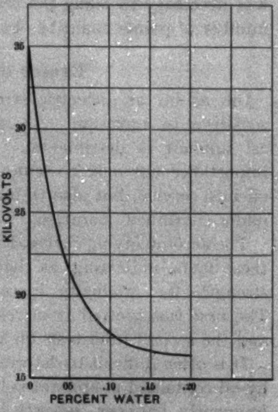

Fig. 9—Influence of moisture on dielectric strength of light oil

A piece of cold glass plate may be held over a sample and the latter heated to the boiling point of water. Any moisture driven off will be condensed on the plate.

Anhydrous copper sulphate is sometimes used, a small quantity being shaken with the oil to be tested. If it contains moisture in any considerable quantity, a slightly blueish color will result.

Still another method is to thrust a red hot nail or piece of wire into a sample of oil. A crackling noise will be heard if moisture is present. If dry, there will simply be a puff of smoke.

A similar test can be made by placing a sample of oil in a small porcelain dish, and heating it over a flame. If moisture is present a sharp crackling noise will result, much the same as with the hot nail or wire just referred to.

Of all the methods which have been used, however, the dielectric strength test is the most satisfactory and reliable. Moreover, it is extremely sensitive so that even the smallest percentage of moisture may be detected.

This last method is the only one which can be recommended as being absolutely sure. The one mentioned just before this, *i. e.*, heating the oil in a porcelain dish is the next most reliable, but even this is not certain. (A number of tests were made on various samples to determine the accuracy of this method, and not more than 60 per cent of the results were correct. It may be of value, occasionally, however, when no high voltage testing outfit is available). The hot wire method would come in the same class.

The other tests mentioned are only of service when large quantities of moisture are present. Otherwise, they are not reliable.

METHODS OF DRYING AND FILTERING OIL

In view of the importance of dry oil, many methods for removing moisture have been devised. Some of these are suitable for laboratory only, and are not practical for commercial purposes. Others are quite satisfactory for use in the shop and testing department, but on account of the expensive apparatus required, cannot well be employed for installation work or in connection with any but the largest power plants. Still other methods have been tried out and then laid aside, either on account of cost of operation or length of time required for treatment. As a result, there are but few methods which are of much service commercially. It may be well, however, to mention all, some briefly, others at greater length, depending upon their importance. The following will be considered.

Drying by means of:

(1) Chemicals,
(2) Heat,
(3) Heat and vacuum,
(4) Heat and air,
(5) Settling,
(6) Centrifugal separators,
(7) Paper filters,
(8) Miscellaneous.

It should be noted here that the first five methods mentioned above, are suitable only for removing moisture, and do not remove dirt or other foreign matter. The next two in the list purify as well as dry. Sometimes one method, sometimes a combination of several methods have been used successfully.

Chemicals. Of the various chemicals used for dehydrating oil, calcium chloride has given the most satisfactory results, although calcium oxide, (unslacked lime) is also used extensively and gives good results. Calcium carbide and metallic sodium, as well as other agents have been tried with varying degrees of success.

The accompanying curves, Fig. 10, indicate the comparative rates at which these materials remove moisture from oil. It will be noted that calcium chloride required seventy hours; metallic sodium 115; calcium oxide 165; and calcium carbide 260 hours, to bring the oil from a dielectric strength of 7,000 volts up to 30,000. (Tests made between ½-in. disks placed 2/10-in. apart.)

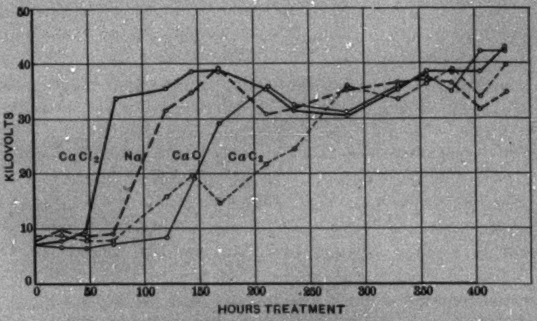

Fig. 10—Effectiveness of oil drying material

Calcium chloride, $CaCl_2$; Metallic sodium, Na; Unslaked lime, CaO; Calcium carbide, CaC_2

The tests were made first by mixing a small amount of water with a quantity of oil, separating into four parts and adding respectively the four drying agents; six per cent by weight in each case. The drying materials were chemically pure, and in order to expose the same surface to the oil, they were broken up into about ¼-in. lumps. The samples were thoroughly shaken and allowed to stand 24 hours after which they were tested.

The process of shaking, allowing to stand, testing, etc., was repeated every 24 hours, until the oil had returned to its initial dielectric strength.

Calcium chloride required the least time of all.

Metallic sodium came next in order of time. Its use, however, is considered dangerous, inasmuch as it unites with water to form hydrogen and caustic soda, and if a large quantity of water is present the reaction might cause sufficient heat to ignite the hydrogen. Moreover, the caustic soda formed dissolves in oil and tends to soften insulating materials, such as varnish or gum compounds.

Calcium oxide required still longer time to absorb the moisture as was also the case with calcium carbide. The latter also has the disadvantage that it gives off a highly inflammable gas, acetylene, when it comes in contact with water.

Continuing the subject of calcium chloride as a dryer, it may be of interest to mention the results of several tests made to determine the best method of utilizing such material for removing moisture from oil in transformer tanks, when the natural circulation of the oil alone is relied upon for bringing all portions in contact with the calcium.

Three tests were made, the oil in each instance being placed in a fairly large sized tank, and maintained at a temperature of about 80 deg. cent. by means of a wire-coil rheostat at the bottom. One per cent of water was added to the oil and thoroughly mixed with it for each of the three trials. In the first trial no calcium chloride was used, the test being made to determine the length of time required to bring the oil back to a given dielectric strength by settling only. In the second trial, a quantity of calcium chloride was placed at the bottom of the tank, and for the third trial the chloride was placed in a perforated metal tube, suspended in the tank midway between the top and the bottom.

At the beginning of each trial, the oil measured approximately 7,000 volts, (tested between ½-in. disks, placed 2/10-in. apart.) The runs were continued until the oil at the top of the tank reached a strength of 50,000 volts, (that at the middle measured 45,000 volts, or over.) Ten days were required in the first instance, four in the second and two in the third. The most effective method used therefore, was that in which the chloride was suspended in the center of the tank. Whenever this method is used, however, care must be taken to provide a suitable receptacle for collecting the water and wet chloride, and yet allow free contact between the fresh chloride and the oil.

A method which gives still better results as regard time required, is one which provides for the forcing of oil through a receptacle containing calcium chloride or calcium oxide, (unslacked lime.) The quantity of oil which can be dried per hour is thus greatly increased. It is usual in connection with this treatment, to complete the process by forcing the oil through dry sand. This removes all traces of dirt and foreign material and prevents any particles of lime which may be held in suspension, from passing through into the receiving reservoir. Bone black or Fuller's earth are sometimes used in connection with this process, in case it is desired to remove coloring matter from the oil as well as other impurities.*

Heat. Heat is frequently employed for removing moisture. It is sometimes applied to the outside of the receptacle containing the oil, and in other cases is introduced by means of steam coils or an electric heater. The last mentioned arrangement is preferable, and is usually more convenient. In all cases the temperature maintained is about 105 deg., or, in other words, slightly above the boiling point of water.

This process at best is slow. It must be watched with great care, and there is always the danger of injuring the oil from over-heating. Long continued overheating will cause a deposit to be thrown down and is also liable to change the nature of the oil by driving off some of the lighter hydrocarbons.

Heat and Vacuum. The danger of the overheating mentioned above may be practically overcome by removing the air pressure from the drying receptacle and employing heat as before. The reason for this is that water boils at much lower temperature in vacuum than ordinary air pressure. Thus, in a 27-in. vacuum, boiling occurs at 46 deg.; in a 28-in. vacuum at 38 deg., and in a 29-in vacuum at 25 deg. cent., etc.

This process may be still further facilitated by allowing dry air to bubble slowly through the oil. The air may be readily freed from moisture by first passing it through some dehydrating substance, such as calcium chloride or unslacked lime.

Heat and Air. Perfectly dry air has also been used to advantage. This may be forced through numerous openings at the bottom of the tank and allowed to bubble up to the surface.

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* Article by S. M. Kintner, "The Treating of Transformer Oil," *Electric Journal*, October, 1906.

The oil in the containing tank may, or may not, be heated, although heating naturally facilitates the operation. The air may be dried by passing it through calcium chloride or other drying agents.

Instead of using air alone, the air and vacuum process may be employed, as outlined at the end of the preceding paragraph.

Settling. When oil contains a large quantity of water it may be gotten rid of almost entirely by allowing it to stand for some time undisturbed. The water as well as some of the impurities gradually settle to the bottom, leaving a dry oil to be drawn off from the top. The process usually requires a number of days, and herein lies the greatest difficulty in its use.

Centrifugal Separation. The different specific gravities of oil and water make it possible to separate the two by centrifugal action. It is extremely difficult to remove all of the moisture by this means, but it serves a good purpose in taking out a considerable portion of it when the oil is extremely damp. The remainder, however, may be removed by means of a filter within the upper part of the machine, so that virtually both steps in the process take place at the same time. The operation may be accomplished by a standard cream separator like the De Laval. The damp oil is fed into the top and passes down into the center of the rapidly revolving element. The centrifugal action forces the water, which is the heavier of the two, toward the outer casing, where it may be drawn off like skim milk. The oil, like the cream, passes into a central chamber and then up through sheets of filtering material into a receiving reservoir, from which it may be drawn off for use. During the first part of the operation, all but about one-tenth of one per cent of moisture may be removed, while the small amount remaining, is taken out by the filter.

Damp oil has in this way been raised in dielectric strength to a value of between 40,000 and 45,000 volts, (measured between ½-in. discs, placed 2/10-in. apart.)

With a medium sized machine it is possible to dry and clarify from 50 to 60 gallons per hour, provided the oil is not in too poor condition to start with.

Paper Filters. It has been known for some time that ordinary filter paper, such as is used in chemical laboratories will allow oil to pass slowly through it, but will not allow water to pass. This principle has recently been employed on a larger scale in what is known as an oil dryer and purifier. This piece of apparatus consists of a press for holding the paper, a pressure pump and an operating motor, together with necessary piping, valves, gauges, etc.

The most interesting part of the outfit is made up of a number of alternate grids, and chambers arranged in such a way that square sheets of blotting paper may be placed between them and the entire device bolted together. By means of suitable channels the oil from the pressure pump is led into the chambers, forced through the blotting paper and finally discharged into the receiving tank. The blotting paper allows the oil to pass, but retains all moisture and impurities thus raising the dielectric strength to values as high as 60,000 to 70,000 volts, (measured between ½-in. disks, placed 2/10-in. apart.)

With a moderate sized press, 600 gallons of medium grade oil may be treated per hour, and twice this amount of light oil, it merely being necessary to replace the blotting paper occasionally, once every half-hour to an hour is sufficient with oil in fair condition.

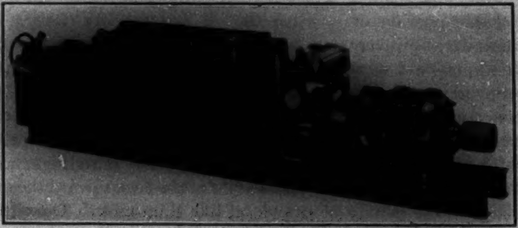

Fig. 11—Oil drier and purifier

Not only can such an outfit be used for first drying and purifying oil before it is introduced into high voltage transformers, but it may also be employed from time to time while the transformers are in operation. In such cases the oil is taken from the bottom of the transformer tank, forced through the filter press and back into the transformer at the top of the tank, this process, of course, being continued until the oil reaches the desired dielectric strength.

The general construction of the outfit is shown in Fig. 11.

Miscellaneous Methods. Capillary action has been made use of to some extent in freeing moisture from oil, also electrostatic force. Sponges have been tried and found to give fairly good results. The expense however is prohibitive, as only the very best grade of sponges are at all suitable. For removing impurities sand gives excellent results. Cheesecloth is also frequently used.

PRESENCE OF SULPHUR AND PARAFFINE

While the presence of free sulphur has an effect on the dielectric strength of oil, the greatest danger lies in the fact that even in minute quantities it vigorously attacks the copper. In time, conductors have been known to be completely severed on account of sulphur alone. It may be detected very readily by dipping a small polished wire into the oil, which has previously been heated, and allowing it to remain until it becomes black. The time required for this to occur may be judged from the following table, which is made up from results of tests on oil heated to 85 deg. cent.

Per cent sulphur	Time required to blacken copper wire
1/10 of 1 per cent	2 to 3 minutes
1/100 of 1 per cent	30 minutes
1/1000 of 1 per cent	15 to 20 hours
1/10000 of 1 per cent	Uncertain

In some oils small amounts of sulphur exist in very strong chemical combination. These however, have not been proved to be deleterious, probably because the combination is so strong that it is difficult to break it up.

As to paraffine, there must be freedom from solid material of this kind in solution; otherwise, particularly in water-cooled apparatus, it might be frozen out of solution and result in clogging of the oil ducts.

INSULATION RESISTANCE AS AN INDICATION OF DIELECTRIC STRENGTH

It has sometimes been thought that insulation resistance of oil is an indication of its dielectric strength. The accompanying curve Fig. 12 will show that this is by no means always the case, unless temperature is also taken into consideration. It indicates what is experienced every day in heating transformers. With increase in temperature the insulation resistance falls very rapidly, while the dielectric strength of the oil gradually increases until conditions become constant.

If moisture is present, in a transformer, for example, the insulation resistance may drop to a very low value when the oil is heated, and then rise for a time as the last traces of moisture are driven off.

It is only safe to assume that everything is dry when the insulation resistance becomes constant and remains so for several hours. Even this final value, though, may be far below that obtained when the oil was cold.

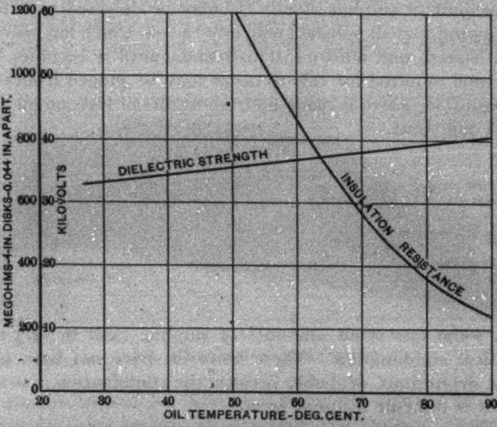

FIG. 12—Variation of dielectric strength and insulation resistance with temperature

SUMMARY

Having first laid down the conditions which an insulating material must fulfil in order to give satisfactory results, we have shown that oil best meets these provided it is used within definite limits. The limits have been found only after making a careful study of the more important characteristics, and it has only been by a systematic investigation of the chemical and physical properties that oil has gradually been made to attain its present state of superiority. It fulfils the ideal conditions so well that it is almost universally used in spite of the fact that it requires unusual care in its treatment and handling.

It is hoped that the paper will aid in giving a clearer understanding of the various properties, not only that such treatment and handling may be made comparatively simple, but also to assist in the selection of oil and its use.

In closing, the writer wishes to acknowledge the valuable assistance received from Dr. C. P. Steinmetz, Mr. A. B. Hendricks, Jr., and Mr. J. A. Capp, all of whom have taken an active interest in the tests, experimental work and study of the results.

DISCUSSION ON "DISRUPTIVE STRENGTH WITH TRANSIENT VOLTAGES", "THE ELECTRIC STRENGTH OF AIR" AND "DIELECTRIC STRENGTH OF OIL". JEFFERSON, N. H., JUNE 29, 1910.

D. B. Rushmore: Mr. Whitehead in his paper says something which is perhaps more true than many people realize: "As a result of the increase in values of transmission voltage, however, and of improvements in high voltage apparatus and line insulators, the electric strength of air has become a limiting factor in the long distance transmission of power." It is only of a very recent period that this has been true. It is, however, of great interest and import. In the somewhat old problem of transmitting power, one obstacle after another has been overcome until at present we are confronted with the effect of the insulating properties of air, and what action will be taken with regard to overcoming the obstacles presented by it is a question of much importance at the present time. Until very recently, line insulators were the limiting feature, and at 60,000 volts the standard form of insulator was operating near its limitations. With the new suspension insulators, however, the line can be insulated far beyond the point at which the dielectric strength of air will stand. The question of altitude in transmission lines is also becoming important, because of the lower dielectric strength of air at the higher altitudes. The physical phenomena which take place when corona has formed are extremely interesting, and a considerable number of points arise in connection with it. For instance, it is not quite clear without fuller understanding, why corona should cease to be formed by the lower voltages than that at which it begins.

The phenomena described in the paper are those which are of immediate interest to many members of the Institute. To take an example, a line which was to operate at 60,000 volts had the design of the insulators carefully worked out so that they would always flash over before puncturing. A number of times, however, lightning punctured these insulators and the dielectric time-lag of air was used to explain the occurrence. Also many operating engineers are familiar with the slight blackening of the bright copper wires in their stations, due to the effect of corona formation.

The problem of how best to perform experiments of this kind is a difficult one. We all like to see the conditions surrounding such investigations as nearly as possible like those under which the application of the results will be made, such as the interesting work carried on by Mr. Mershon some years ago on outside commercial lines. It is, however, extremely difficult to obtain exact data in this way, and it would seem that the basis for our engineering recommendations must to a large extent be the result of experiments carried on in the Laboratory.

The relation of power or energy to breakdown or ionization is not clear, and the effect of frequency on such dielectric failure still remains a subject for discussion. The point most deserving of attention is that the future progress of the art depends very largely on the results of the study of the properties of dielectrics. The characteristics of this class of material bring about the limiting features in high voltage power transmission.

V. Karapetoff: Those familiar with the history of the theory of elasticity and of the mechanical strength of materials will find it quite similar to the history of practical electro-statics. During the early stages of the development of civil engineering the engineers who needed to know the strength of columns, bridges, etc., tested them in their actual complicated shapes. The result, therefore, did not characterize the materials, but only certain objects of definite dimensions made out of these materials. Knowing the strength of a column or of a beam of a certain size, it was not possible to predict the strength of a column or of a beam of a different cross-section and of a different length. Then, gradually, a theory of resistance of materials was developed and formulae established into which the elastic coefficient of a material, the dimensions of an object made out of this material, and the given forces entered as independent factors. The next stage in the theory was to combine various stresses and to combine the resultant strains. In most structures and parts of machines there is usually more than one set of stresses (for instance a normal stress and a shear), and unfortunately stresses are combined according to a different law than the resulting strains. Finally the fact became clear that it is the resulting *strain* and not the stress that limits the safe load of a piece of material—I am speaking of mechanical strength now—no matter by what combination of stresses the strain is produced. As the last step, the theory was extended to include the action of *dynamic* loads or what we call in electrical engineering *transient* loads. In bridges, in reciprocating engines, and in the many other cases loads are not steady, they are intermittent; kinetic energy and inertia enter therefore as disturbing factors.

A similar development took place in applied electrostatics. Our predecessors started with a theory of charges acting at a distance. Naturally, with such a wrong assumption, not much progress was made, because the phenomena take place in the dielectric and not on metallic surfaces.

After Faraday and Maxwell had cleared the way for a correct interpretation of electrostatic phenomena, and after it had become necessary for engineers to take into account the dielectric strength of materials, a new impetus was given to electrostatic experiments. But as in the case of early experiments on columns, beams, etc., " practical " electrical engineers still use electrodes of all kinds of fancy shapes, from which the dielectric strength of dielectrics proper cannot be conveniently calculated. Knowing, for instance, the striking distance between two pointed electrodes, it is impossible to calculate the striking distance between electrodes of a different shape, or to determine the critical voltage with the same electrodes at a different distance. The question is, however, being gradually put on a more rational basis; it is at present clearly understood by physicists and by many engineers that the striking distance per centimeter of air-gap between needle points really does not mean much, as regards the dielectric strength of air. Experiments must be preferably made on large (practically infinite) parallel plates, in which case the stress in the dielectric is the same at all points. Or, else, electrodes must be used of such a shape that the true strains (critical dielectric flux density) can be calculated from the striking distance. Concentric cylinders are convenient for the purpose.

I wish to refer to the sketches Figs. 1, 2 and 3 of Mr. Tobey's paper, which illustrate my point. The sketches show the difference between a uniform dielectric field in the case of parallel plates, and non-uniform fields in the case of sharp points on spheres.

In a non-uniform electrostatic field it is necessary to consider the actual stresses from point to point, because the air is not broken down simultaneously at all points. It is possible to break down certain portions of the air nearest to the electrodes, to ionize it, to make it a conductor, without producing a jump-spark. The air so ionized becomes a part of the electrode, so that the break-down finally occurs between new shapes of electrodes. This leads to the consideration of the quantity usually called the electrostatic capacity between two electrodes, but which ought to be more properly called the *permittance of the dielectric*. By using proper values of permittance and "permittivity" of the dielectric, calculations of the dielectric strength of insulation are put on the same scientific bases as calculations of conductors of non-cylindrical shapes.

At present we are not yet advanced far enough to be able to calculate the distribution of electrostatic stresses in all cases, but in the simplest cases, for instance, such as is presented by Dr. Whitehead, or in the case of two spheres, it is possible to calculate the actual stresses and their distribution. It is not the average strength of the air, considered as a mass, that interests the engineer, but the *weakest point* at which the air breaks down. The safety of insulation must be considered with regard to this weakest point, the same as the civil engineer figures out the factor of safety of the weakest part in his bridge. And fortunately the electrical problem is simpler than the corresponding problem in the theory of elasticity, because there we have two kinds of stresses, normal stress and shear, while in dielectrics there is but one kind of stress. I do not know what kind it is; perhaps it is some kind of shear between positive and negative electricity; at any rate we have to consider only one kind of stress.

Now we come to the last stage, the same as civil engineers had to face, namely, the effect of dynamic loads, of transient voltages. The paper by Mr. Hayden and Dr. Steinmetz represents the results of a pioneer investigation in this field. Let us consider their experiments in the light of a mechanical analogy, that of an elastic rod or a column suddenly subjected to a normal stress by a released weight. Is it correct to say that the weight is instantly balanced to its full extent by elastic forces in the rod? To me such an assumption contradicts the laws of mechanics of elastic bodies.

In order to produce an elastic reaction a strain or a deformation must first occur in the rod. The rod can resist only (1) as the result of such a strain (elasticity), or (2) by opposing an acceleration of its parts (inertia). In the case under consideration there is no initial strain in the rod, and in order to produce it parts of the rod must be accelerated layer by layer. At the very first instant the load is balanced by a very high acceleration of a very small part of the mass of the rod adjacent to it; then the next layers are accelerated so that we get the effect of a travelling compression wave. Only after a certain displacement has taken place the load is balanced in part or in full by the elastic forces. Hence this paradox that with a very short application of the weight, that corresponds to our transient voltage, the column or the rod can seemingly support without being destroyed a heavier load than with a load applied gradually. Is it not more logical to suppose that the molecular strain, the *actual strain* at which the material breaks down, is the same in both cases? Only in the case of a transient application a part of the load is balanced by the acceleration of the mass and has no time to produce elastic stresses, before the load is removed.

It seems to me that the results obtained by Mr. Hayden and Dr. Steinmetz must be interpreted in the same light. I cannot conceive how a voltage of say 100 kilovolts can be applied suddenly to a neutral dielectric, that is to say to a dielectric which is not strained. The action must be equal to the reaction, and a dielectric which is not strained can produce no electrostatic reaction. It can react only electromagnetically, by means of displacement currents in it, or in the other parts of the circuit. I am willing to grant that the voltage calculated by the authors was actually induced in the high-tension windings of the transformer, but it does not follow from this that at the very instant of the closure of the primary switch this full voltage acted across the air-gap, producing *static* stresses in the dielectric. The electromagnetic inertia effects are predominant at the first instant.

The slope of the voltage wave is very steep at the first instant; therefore, even a very small magnetic leakage between the two windings of the transformer, a leakage negligible with ordinary frequencies, must have produced an enormous counter-electromotive force. I am inclined to think that at the first instant the voltage between the electrodes was practically equal to zero. The unstrained dielectric acted as a short-circuit, and the applied voltage was balanced by the reactance counter e.m.f. We must remember that the rush of current at the first instant is tremendous, in order to produce the required displacement in the dielectric. There could have been also a considerable magnetic field in the dielectric proper. We have in reality a much more complicated phenomenon, *electromagnetic* as well as *electrostatic*, than it appears on the surface. It is hardly scientific to say that we simply have 100 kilovolts momentarily applied to air or oil, and that momentarily these dielectrics can support more than with a steady application of the voltage.

We must be particularly careful now, when we just begin to understand the full meaning of these phenomena, not to describe them in a "short-hand" way, but to specify carefully the actual physical relations. Without this precaution, busy practitioners are only too prone to misunderstand the results, and to apply them in cases for which they were not intended at all.

Percy H. Thomas: Professor Whitehead's paper suggests many questions that I presume he is not in position to answer as yet, but there are a few points which I think would clear up some matters.

Professor Whitehead has apparently made a very desirable advance in having devised a method for the study of corona and allied phenomena in which he can eliminate all variables which he does not control. His tests, being laboratory tests, and made under somewhat limited conditions, do not tell us everything about corona, but apparently he has succeeded in controlling all the variables actually present in his tests, so that he can absolutely reproduce his results on different days and under quite different circumstances. With such a result realized, it is possible to add another known variable, and get its effect, and so on step by step.

I ask Dr. Whitehead if he will tell us something concerning the electrical conditions at the ends of his tube.

I would ask Dr. Whitehead if it is possible that the peculiar action of small wires in giving the apparently high dielectric strength for air could be due to the fact that near the surface of the small wire the strain is changing rapidly. That is, the volume of air that is subjected to the maximum stress is very much more limited than where the wire is larger; the potential gradient being much sharper in the case of the small rods.

I would ask whether the air which passes through the tube coming from the wire at the time of the formation of corona is ionized in the sense that there are positive and negative charges therein equally balanced, or whether it comes away with a predominant positive or with a predominant negative charge, and if so, which? Also whether he has tried any other gases than air.

Another point, in the visual observation of the corona through oscillographs, has he observed both positive and negative waves, direction being taken with reference to the test wire—that is, were observations made with the positive potential on the inner wire or the negative potential on the inner wire, or with both? If so did any difference appear?

One other question—I would ask how the actual arc, that is, the complete break down, follows after the ionization first begins, that is how wide a range of voltage, for example, exists between the point where you can first observe a rapid dropping of the electroscope, and formation of the actual arc.

A. E. Kennelly In regard to one particular point in these very interesting papers, Dr. Whitehead emphasizes the fact the electric intensity at which disruption appears is greater for small wires than for large wires. A suggestion for the reason of this remarkable phenomenon may be offered tentatively. We know, referring to the properties of the magnetic field for a moment, that a small magnetically polarized iron particle, or iron filing, is not acted upon by any magnetic force of translation—any bodily moving force—when subjected to a uniform magnetic field, or a magnetic flux distribution acting in parallel straight lines. There are forces of rotation, couples, or torques, but no forces of translation. When, however, the magnetic field is not uniform but divergent, the iron filings are subjected to translatory forces as well as couples, and are pulled bodily towards the denser parts of the field. This effect may roughly be described by saying that the magnetic pull, in the denser part of the field, on the attracted pole, is less than the opposing push, in the weaker part, of the field on the repelled pole. In fact, we know that the pull of a divergent field $\mathcal{H}$ upon a spherical iron particle or spherical iron filing depends upon the product $\mathcal{H} \cdot \frac{d\,\mathcal{H}}{d\,s}$, where $\frac{d\,\mathcal{H}}{d\,s}$ is the greatest space rate of change of the field.

Now returning to the electric field, if we may assume that a molecule of gas subjected to an electric field is polarized thereby, then the molecule will be subjected to a couple or aligning force; but if the electric field is uniform, there will be no pull, or force of translation, on the molecule. If, however, the field is convergent, a force of translation will exist as well as the couple, and the molecule will be pulled towards the denser part of the field. In the case of an electrified round wire, the field will be radially divergent from its surface, and the divergence will be numerically greater, the smaller the wire's diameter. We should, therefore, expect air-molecules to be drawn in towards the surface of the wire, and to crowd together near that surface, just as though the atmospheric pressure were locally increased in this vicinity. If such a local increase of air-density occurred around and near the surface of a wire, the electric intensity required to produce disruption should be increased, as it increases with the atmospheric pressure, and the increase should be greater the smaller the wire. I tried the experiment recently, with Dr. G. W. Pierce, since reading Dr. Whitehead's paper, of electrifying a two-millimeter wire running down the axis of a glass tube and observing whether the pressure of the air, within the tube as a whole, became thereby altered with respect to the pressure of the air outside the tube. We were unable to detect any such effect. Consequently, although the effect above suggested might occur, and might yet be masked in this experiment by opposing actions, yet it must be admitted that thus far, the suggestion is not supported experimentally.

W. H. Pratt: There is one suggestion which comes to me in connection with the second paper, which has read. The results quoted with moist air are apparently in disagreement with certain other measurements which have been made. May it not be that moist air, as we find it in the open, at times contains electric nucleii due to the partial re-evaporation of condensations that have occurred around these electric nucleii, and hence the moist air, at such times, is really somewhat conducting, whereas in the experiments that were outlined, the moisture was added to the air in such a way that it certainly would not be expected to be conducting.

E. E. F. Creighton: Two of the big problems in the transmission and distribution of electrical energy are the lightning protection of the transmission circuit and the suppression of troubles from internal surges of electrical energy. The dielectric spark lag and the spark energy enter into both problems and most vitally in the latter. Speaking of internal surges only, it has been noted here and there all over the country that transformers and generators would fail at some internal part of the winding. On any particular system these failures are rather infrequent, but the aggregate is considerable. Some time ago this problem of internal surges was confused by the presence of end turn effects. Modern designers have eliminated the end turn failures by heavily reinforced insulation. This leaves the problem of caring for internal surges distinct and prominent. The conditions of cost are not such that a designer may place everywhere in the windings, as he does on the end turning, an insulation that will stand a test pressure of 6,000 to 20,000 volts when the dynamic voltage normally present is only ten to twenty volts. The amount of energy in these internal surges is usually small. The excellence of a design taking these factors into consideration would never be casually apparent, yet they would be vital. With these practical features in view, the theoretical and experimental studies made by the authors assume a great importance. Careful measurements are the life of further progress. A simple method of test is given which can be extended easily to further studies.

The speaker has had occasion to study a particular feature of the dielectric spark lag of protective apparatus, with the object in view of getting rid of it. We were surprised to find lags extending to several seconds. To the speaker's knowledge this long lag has never been observed before. These data have a strong bearing on the subject of the paper. Among several other things, the dielectric spark lag depends on the excess voltage above the voltage which would cause a spark to pass if applied for a long time, theoretically for an infinite time. For brevity, call this, excess voltage the super-spark potential.

As would naturally be expected, the relation between the super-spark potential and the time, is hyperbolic. For very great superspark potentials the time interval before the spark passes becomes only a few milliseconds, or may even go down into the microseconds.

In the curve herewith reproduced the measurements were taken by the simple method of the oscillograph. Direct current potential was applied to a gap and the time interval measured between the application of the potential and the beginning of the current in the spark. The points of slight super-spark potential deviate very little from hyperbolic curve—in this particular case $x\ (y-23) = 1780$. (See Fig. 1). But the points at considerable super-spark potential are somewhat variable, showing an erratic behavior not understood at present. At only 35-volt super-spark potential, the lag is 200 milli-seconds. At 250-volt super-spark potential, it is 20 milliseconds. At 300-volt super-spark potential it is 6 milliseconds.

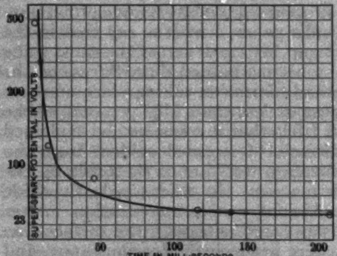

FIG. 1.—Super-spark potential curve. The points are taken by measurement and the curve is the hyperbola $x\ (y-23) = 1780$

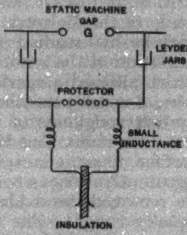

FIG. 2

The asymtote to the curve is 23 volts above the spark potential at an infinite time of application. This may have been due to difference in conditions of tests as this value was taken some time previous to the other readings.

The dielectric-spark-lag was demonstrated by another test using alternating potential. The spark-potential for continuous application was less than the peak value of the alternating potential, yet under these conditions it was not possible to spark across the gap. Successive alternations apparently deionized the gap. At any rate the time of application of super-spark-potential was not sufficient to cause a spark and the successive impulses were not cumulative.

The obnoxious effect of the spark lag on the operation of lightning arresters was noticed first, years ago, in taking equivalent needle-gaps and other direct measurements of the value of lightning arresters.

The gap at *G* of a static machine requires a certain pressure to spark. (Fig. 2). This determines the value of pressure that will appear at the protector. At the terminals of the protector is attached the insulation to be protected. Between the protector or lightning arrester and the insulation a small amount of inductance is placed to imitate circuit conditions. When the pressure at *G* was as high as 100,000 volts, the insulation was not injured as the spark took place quickly at the protector. When, however, the electric pressure at the gap (*G*) was relatively small, in one case about 3,000 volts, the insulation was punctured. The greater time lag of the protector allowed the charge to pass beyond into the insulation and although the spark sometimes took place in the protector, it occurred too late to give protection.

In regard to Dr. Whitehead's paper, I wish to say that in the study of the dielectric spark-gap, we came across the same thing that he has studied in what he has named dirty wires, or the oxidation of the wire. We had ionization taking place on wires which allowed a spark to pass at less than fifty per cent of the normal spark potential, and I felt that it could not be explained by any roughness of the surface. It seemed evident from the tests we made, that the ionization was due to the oxide on the surface, in some inexplicable manner. In other words, the oxide apparently causes a considerable degree of auto-ionization. After we removed the oxide it disappeared, although the surface was equally rough. The tests were made in hydrogen vapor, and consequently the oxide on the copper was reduced by the passage of an arc over the surface. These results are suggestions although the phenomenon may be different from the effect of duty copper wires in air.

J. C. Lincoln: There is one question I would ask Dr. Whitehead. In the diagram of his apparatus, he shows a wire in the medium which is controllable, and I take it from the diagram that there is passed through the medium an alternating voltage, and therefore that the ionization, such as there would be, would tend to produce positive and negative ions in the tube, and in that way the ions are passed across the indicating instrument and some kind of an indication is given. Apparently either the negative or the positive ions are in preponderance, and I would like to know which did preponderate.

Charles F. Scott: I want to say a word in appreciation of the three papers which have been presented, and the work they represent, and the valuable part which these papers will play in the progress of the art.

In going into a new field like this high voltage field, there is good deal of pioneer work to be done of two kinds—work in the laboratory and work in the field, theoretical work and practical work. Very often these alternate. First we take one kind of step and then the other. Dr. Whitehead enumerated several papers which have been presented to the Institute, which are preliminary to his, and form a series. In running over these papers, I note the first one is on the dielectric strength of air by Dr. Steinmetz, a laboratory paper; next is the Telluride test by Mr. Mershon, which was a field test; next is the paper by Professor Ryan, a laboratory test; next follows a Mershon paper, giving field tests, and now the Whitehead paper, a laboratory paper follows. The next thing on the regular schedule would be to have another paper from Mershon.

Harris J. Ryan: Dr. Whitehead's paper is a most valuable contribution to the subject.

The writer agrees with the author that "secondary ionization is the cause of initial breakdown and formation of corona." For out-door conditions he prefers the terms "native" ionization to "antecedent" ionization as used in the paper. He differs from the author in the conclusion that native ionization enlarges the effective terminal until the stress (intensity) at its surface falls to the ionizing value. *Native ionization strengthens the stress near the terminal and diminishes the distance to the ionizing zone. This distance is required to accomplish the process of general ionization by collision, i.e. the formation of corona.* At a stress of 76 kilovolt-in., or 30 kilovolt-cm., ions travel nearly one inch in 0.0002 second. The region about the electrode enclosed by the zone in which the corona starts contains mostly native ions of opposite polarity. Such ions will strengthen the stress and lessen the striking distance to the corona forming zone.

Recent studies of the normal in-door air show that the value of J. J. Thomson and the one in which the author of this paper expressed confidence, a year ago, is correct, namely, 76 kilovolt-in. There is much evidence that 40 kilovolt-cm. as given now by the author is too high for normal in-door air.

The rapid outward spread of the stress from the surface of a small conductor and the greater concentration of native ions combine to make the striking distance to the initial corona zone shorter. Since the initial corona zone always forms in the normal air at 76 kilovolt-in., the net result is that the surface stress of the conductor rises as the initial corona striking distance falls.

In regard to the statement "In view of these discrepancies one naturally turns to Mershons' method for measuring the loss as a possible source of error." A careful study of the methods used at Niagara and recent laboratory tests have convinced the writer that Mershon's methods and results are correct. There are no real discrepancies. The surprises are due mainly to the larger native ionization at the Falls. Mershon's Niagara corona zone stresses go below 76 kilovolt-in., because of irregular distribution of stress about parallel conductors worked with alternating high-tension; this irregularity is produced and enhanced by the larger supply of native ions occurring at Niagara Falls. The vapor-product is an indirect evidence of their quantitative variation.

R. D. Mershon: Referring to the paper by Mr. Hayden and Dr. Steinmetz, I would ask them to make clear how they determined the energy available at the spark gap; how they found out what energy was effective.

C. P. Steinmetz: We did not determine it, do not know it.

R. D. Mershon: Then it seems to me it is pretty hard to arrive at any definite conclusion.

C. P. Steinmetz: The only conclusion is the total energy supplied to the apparatus, hence the energy at the spark gap must be less than that. We give only the energy limit.

R. D. Mershon: The question of energy is related to that of voltage. I do not see how you can have any idea of the voltage finally impressed upon the dielectric.

C. P. Steinmetz: I will answer that in the final discussion.

R. D. Mershon: Referring to Dr. Whitehead's paper, the questions and doubts he raises in regard to the accuracy of my high-voltage measurements at Niagara are all of them questions and doubts which I myself raised at the time the results were obtained, and which I feel were resolved by the careful tests made of the accuracy of measurement. We tested out the method of measurement in every way possible and in consequence of these tests I am well satisfied that the method of measurement is a reliable one, and that the results obtained are substantially correct. I feel confident the accuracy of the measurement is within 5 per cent, and probably much closer than that. Reference to my paper will show the kind of tests made, and the method of making them.

The apparatus used at Niagara was not that used at Telluride. It was of the same kind, but better designed and executed. At Telluride I had a 1,000,000-ohm resistance with which to test out the accuracy of the measuring apparatus. At Niagara no such resistance was available, but in view of the closely checked results obtained at Telluride making use of the resistance, together with the fact that the Niagara apparatus was an improvement on that at Telluride, and in view of the results of such check-readings as could be taken at Niagara, I have no suspicion whatever of the accuracy of the Niagara apparatus and the results obtained with it.

Dr. Whitehead says:

> "Since Mershon's observations appear to have been taken in all seasons, it may be stated that a range of temperature of 35 deg. cent. and a pressure of 25 mm. of mercury, and an error of 5 per cent in the critical point as taken from the curves, would give a range of critical voltage as wide as that attributed by him to moisture".

I judge from this that Dr. Whitehead thinks the relation I found between critical point and vapor product may be the result of a series of errors. If this is the case, it is curious that these errors should have occurred so consistently over a year and a half, during which time measurements were taken almost every day.

I do not see how it is possible that any errors in our observations or in our method of measurement could account for the variation of critical point with vapor product. The effect was entirely too marked to be so accounted for. Before we discovered the relation between loss and vapor product, we would sometimes get consistent results over a period of several days, and then the results of the next day would be all out of line. It even happened at times that of a set of observations all taken on the same day the results would be erratic and entirely inconsistent. But all these readings, when interpreted by means of the vapor product, came together and were consistent; the results of different days came together; discrepancies occurring on the same day were reconciled. So I cannot conceive of the relation referred to as being in any way due to errors in either measurements or apparatus.

In this connection I would call your attention to the facts brought out in one of the other papers here, relative to the very small amount of moisture necessary in oil in order to enormously change its dielectric qualities. In what condition does that moisture exist in the oil? Is it water, or vapor? It certainly must be very finely divided, at any rate, for it is uniformly distributed through the oil. This may have a considerable bearing upon the loss in air due to moisture; a loss entirely aside from the so-called ionization loss.

The only error that I can conceive of as possible, due to the method of measurement, would arise from phase displacement in the measuring apparatus itself. The tests made of the apparatus, as detailed in my paper, seem to me to pretty clearly show that there was no such error, or at any rate it was not great enough to account for the discrepancies, if you may call them such, between my results and those of Professor Ryan and Dr. Whitehead.

I would call your attention to the fact that the results obtained by Dr. Whitehead, and to a considerable extent, the results obtained by Professor Ryan, are not necessarily comparable with my results. I did not investigate the matter of ionization. I investigated the point at which the loss between outdoor transmission line conductors begins to rise rapidly, which point I called the critical point. I do not think this loss is necessarily all ionization loss. It seems to me it may include losses other than those due to ionization. The results of Professor Ryan and Dr. Whitehead were obtained under laboratory conditions. My results were obtained under engineering conditions. I do not believe we are safe in applying the results of laboratory investigation to the engineering problem, unless we can check up these results under engineering conditions.

There are too many other elements which may enter to modify laboratory results as applied in practice.

What I have said applies to the conclusions. Conclusion 5 says, " Water vapor or moisture has no influence on the electric strength of air. Increasing moisture content probably lessens the loss above the critical voltage ". That depends on what you mean by the critical point. If you mean the point at which ionization begins, the statement is possibly true, but if you mean the point at which the loss between the wires of a transmission line begins to rapidly ascend, I do not agree with that at all. Similarly with regard to Conclusion 6—" There is no loss through air until the critical voltage accompanied by ionization and corona is reached ". I believe there may be a loss below the critical point, as I have just defined it, and that this critical point does not necessarily correspond to the inception of ionization.

Now, as regards Conclusion No. 10: " The corona has high conductivity, and most of the loss takes place beyond it ". I do not remember anything in the paper which would appear to justify this conclusion. If there is, I shall be glad if Dr. Whitehead will bring it out more strongly.

Referring to Mr. Tobey's paper, Fig. 7 would be much more interesting if the melting point of the oil were shown, and it is to be hoped that in closing Mr. Tobey will give us the melting point. This curve presents some facts in regard to which I have often wondered. I have been afraid sometimes that if the oil in transformers was allowed to solidify, due to cold, we might get into trouble, but according to this curve we are safer with the oil solidified than with it in its normal condition.

C. P. Steinmetz: First, to answer some questions regarding our paper—the energy values, are, as stated in the paper, not the energy appearing at the spark-gap, but are the total amount of energy supplied to the system through the transformer, and, as stated in the paper, the actual energy supplied to the spark-gap probably is only a small part thereof, so that these values merely mean the upper limit of energy, which is sufficient to break down the gap, and probably much less energy will be enough.

As regards the question whether the voltage was actually at the spark gap or not, we carefully looked into the matter and came to the conclusion that this voltage is there, at least approximately this voltage, as near as it was possible to judge. Mathematically, I gave the reasoning in the appendix, which shows how we calculated the voltage which appears at the secondary terminals and thereby at the spark-gap. We know if there is one thing where experiment and calculation agrees, it is in transient phenomena, provided you consider all the factors involved in the problem.

There are two factors which have not been included in that mathematical calculation. One is the variation of the inductance; the second is the capacity of the secondary circuit. It can easily be seen that the variation of the inductance with the voltage has no effect on the voltage, but merely modifies the shape of the voltage curve of the secondary. There remains then the consideration of the secondary distributed capacity. From the constants of the transformer, its estimated resistance, inductance and capacity, it appears obvious, that the effect of capacity could result only in an oscillation, not in a steady change, that is, that at the beginning of the impulse there might appear and probably does appear an oscillation superimposed on the steady discharge curve, calculated in the appendix. Such oscillation may be either limited to the high voltage circuit, and then be of very short duration or small energy, or it may extend into the primary circuit.

In the paper we gave evidence that such oscillation did not extend into the primary circuit, by changing the resistance of the primary circuit, increasing the non-inductive resistance of the primary supply circuit nearly a hundred-fold, and getting the same result. It is obvious if there is any oscillation taking effect in the primary, that by increasing the resistance of the oscillating circuit nearly one hundred-fold, from about ¼ ohm to 26 ohm, the oscillation must be enormously reduced and damped out, and we found the same transient discharge. I believe, however, there was in the high potential secondary circuit an oscillation superimposed on the exponential curve of the calculated voltage ratio, but of extremely short duration, and as the entire effect is a transient, you see that an oscillation of still much shorter duration at the beginning of the effect, could not well be expected to have an appreciable effect. It is, however, desirable, and we hope some time to be able to carry out corresponding investigations by some other method of producing the transient voltage, and thereby being able to determine exactly the amount of energy existing at the spark-gap.

A most interesting paper we have in the next paper, that by Dr. Whitehead, which I consider as extremely valuable and important at present. I may say, indeed, that we had intended to make the same investigation, even assembling apparatus of the same kind, a conductor in the center of a tube, and measuring the beginning of the breakdown by an electroscope. We expected to carry that investigation a little further, that is, to lower air pressure, so as to study more carefully the effect of higher altitudes, since we know that transmission lines at the present time extend to altitudes where the air pressure is appreciably reduced.

There is only one point in Dr. Whitehead's paper, concerning which I do not agree with him, and that is his opinion that the explanation of the apparently greater breakdown strength of air with small wires cannot well be given by the assumption of the zone of condensed air around that wire. We know, and it can easily be shown physically, that all solids are surrounded by a zone of condensed air, and a rough calculation will show that the densities of this air at the immediate neighborhood of the conductor, by gravitational or molecular attraction, may reach considerable values. This phenomenon of the great increase of disruptive strength of air close to the solid terminals I observed and gave the explanation, that it is due to the condensed layer of air, some years ago, I believe in the paper which I read on disruptive strength before the Institute in 1893. There I found that in testing very small air gaps the disruptive strength very greatly increased, beyond that observed in the case of larger air-gaps between parallel plates.

As we know, Professor Ryan has very carefully looked into this effect, and in his paper of 1904 gave it a numerical value. I believe it would be very interesting, first, to take his numerical value of the layer of condensed air, and reduce Dr. Whitehead's tests by this assumption, thereby seeing whether we do not get a greater constancy, and then, inversely, from the data of this test, calculate how thick a layer of condensed air we have to assume to get constant break-down strength of the air. It is reasonable to assume that the layer of air is not the same, but decreases with decreasing diameter of the wire, due to the effect of divergence.

If there exists such a layer of condensed air, the result would be that the initial break-down occurs, not at the surface of the conductor, but at a small, though finite distance from the conductor surface, and with the increasing voltage the break-down extends outwardly, but also extends inwardly towards the conductor, and at a second higher voltage reaches the conductor.

This gives a second point in the curve where a change of the phenomenon might be expected to occur. It is very interesting to realize that with our increasing knowledge of the phenomena of disruptive strength, we are more and more impressed with the similarity of the electro-static strength, and its laws and phenomena, with the laws and phenomena existing in the case of mechanical forces, as pointed out also by Dr. Karepetoff. Only I do not agree that the electrostatic phenomena are simpler than the mechanical, due to the absence of shear, but there is very good evidence which makes it probable that electrostatic shear also exists, because at the edge of the electrostatic field, where the electrostatic field very abruptly changes, for instance, at the edge of two parallel plates, there is a very much greater disruptive force; although the potential gradient would be the same, and there is some evidence qualitatively, though not sufficient quantitatively, that not only the disruptive potential gradient, but also the abrupt variation of the potential gradient causes a breakdown. This was discovered first in the old Ferranti system in London, England, in bygone ages, when the cables had the unhappy habit of breaking down at the edge of the insulation—where there is an abrupt change in the electrostatic field, that is an electrostatic shear, and it is so well known in the industry that we always carefully avoid abrupt changes of the electrostatic field, for instance, at the end of lead covered cables taper the field, etc. Experience has shown that if we allow too sudden variations of the static field, we break the insulation down, although the insulation is just as thick as where the field is uniform.

Originally when electrostatic phenomena were first investigated, they did not appear to agree with a constant breakdown strength of air, but gradually the phenomena lined themselves up in the direction of law and order, pointing towards a definite strain which air will stand, and beyond that will break down, and what we here are mainly interested in is the range beyond the break down, that is the phenomena beyond the electrostatic elastic limit of insulating material, where the phenomena have ceased to be reversible and become irreversible. It is the same thing in mechanical engineering, and we shall listen still to a paper dealing with an analogous problem in the mechanical force. This is an extremely interesting field, but the difficulty of exploring it is the same as in the case of almost all phenomena—you never find in nature a clear cut case of the action of one phase or one form, you always have it complicated by numerous other conditions, forces or phenomena which are existing as secondary actions, and practically most of the work of the electrical engineer and other engineers consists of a very simple calculation of the theoretical condition, and then he must calculate and estimate the secondary actions which modify, and sometimes entirely obscure the primary action of the phantom apparatus under phantom conditions.

The most important secondary actions in electrostatic phenomena are:

First, the phenomena of the effective terminal. That is, when we have electrostatic fields, the terminals of the field are not the solid terminals, the needle points or spheres, but are made up of that space surrounding the solid terminals within which the air or space is broken down, has passed beyond its elastic limit and is more or less conductive. Between needle points, even at extremely low voltages, the break down strength is excedeed at the points, nevertheless the spark discharge does not occur until much higher voltages are reached, and when it occurs it is not a discharge between needle points, but between these effective terminals, these approximately spherical spaces of conducting or ionized air.

The study of that phenomenon mathematically is rather difficult; is not as simple as it appears. We can easily consider the electrostatic field with its force lines and equi-potential surfaces between needle points or spheres, and then see at a given voltage what is the equi-gradient surface which corresponds to the break-down of air, and all the air space inside of this surface would become conductive. But as soon as the space becomes conductive up to the equi-gradient surface, the equi-gradient surface becomes an equi-potential surface, while it is not an equi-potential surface in the original electrostatic field. That means the distribution of the lines of force changes and the entire field changes and the problem is to find that equi-gradient surface which at the same time is an equi-potential surface, and has the particular numerical value of the break down strength of air, and that is rather a more difficult problem.

The second phenomenon is the layer of condensed air which surrounds the solid material. The result is that the disruptive strength at the surface of the terminal is different from what it is in the space at some distance. At atmospheric pressure it is very much higher. The result of that would be, as I stated, that the initial break-down occurs at a voltage corresponding to, not the break-down gradient at the conductor surface, but at the space some distance away, or, in other words, it occurs when the ratio of the electrostatic gradient to the density of the air has reached the maximum at some point at some distance from the conductor. This also requires further theoretical investigation, which probably can be done, because we know the law of gravitation, and the gas laws, and the layer of condensed air could be calculated.

When you have electrostatic forces acting, the phenomena may be expected to be complicated still further, as Dr. Kennelly pointed out, by the electrostatic attraction, which changes the density of the layer of air and its volume.

Lastly, and one feature which we usually overlook, is the resistance of the conducting space of the effective terminals. It is not correct to say that the space within which the air is broken down and which forms the effective terminal, is a perfect conductor, but it has some resistance, and therefore quite considerably modifies the phenomena. To illustrate it by the discharge between needle points—we have a discharge occurring between these effective conductors, spherical spaces of ionized air, but these spaces are not perfect conductors—they have a certain resistance, and the resistance has the characteristic of gas resistance, that is, it increases enormously with decreasing current density. Now, the current density depends on the size of the conducting terminals, the volume which has to be ionized, and also on the frequency, and you see, then, within this range, until you have reached so large conducting spheres, effective terminals, that the amount of current required for ionization is large enough to give a negligible resistance, the frequency as well as other features, have no effect. That is very markedly shown in the striking distance curve between needle points. Theoretically, we can calculate it, allowing for the effective terminals, the ionized air space, and no matter what allowance we make we can easily show that the striking distance between needle points should be a straight line going through the origin. Now, the actual curve, as we found it by test, is given in the paper in the 1898 TRANSACTIONS, at 125 cycles; it differs from the straight line at lower voltages. More recent tests at 60 cycles seem to show a curve in which the deviation from a straight line extends to somewhat higher voltages, and there seems to be some evidence which makes it probable that at extremely high frequencies, 100,000 cycles, the curve remains straight practically down to zero, that is, is the true theoretical curve. The cause of this deviation from the true theoretical curve seems to be the resistance of the effective terminals which, within that range, are still so small that the current consumed by them is sufficiently low to give a resistance, consuming a voltage comparable to the voltage between the needle points. At higher voltage the space ionized is so large and the current absorbed is so great that the effect has disappeared. That is another secondary phenomenon which requires consideration.

Again, we really do not observe the break down voltage, or the elastic limit of air directly, but always indirectly by different methods, and there is no evidence that the point we observe by different methods is the same point. We get it by the disruptive discharge. We get it by observing the beginning of ionization, as described in Dr. Whitehead's paper. We get it by the corona. We get it by measuring the energy loss in the conductor as in Mr. Mershon's paper or Mr. Ryan's paper. Then we get it by the increase of capacity of the conductor, at the voltages where the corona spreads out and increases the effective conductor. There is no reason why the different methods should really give you the same point. As soon as the air begins to break down anywhere in space, an irreversible process occurs. The energy consumed by it is not returned. It means at that point the energy loss in the electric system must appear. If we could measure the beginning of the energy loss exactly, which is an extremely difficult problem, we could show the beginning of the energy loss, the beginning of the break down.

As there is a layer of condensed air, that initial break down occurs at some distance from the conductor, and the conductor, therefore, is surrounded by a zone of conducting air which is separated from the conductor by a layer of compressed and insulating air. There is no conduction of current from the conductor into the ionized air region until a higher voltage is reached, when the zone of disrupted air spreads to the conductor and current begins to flow into the zone. It appears possible that the point where the capacity of the conductor increases is not the point where the initial break down occurs, but is the point where the zone of broken down air gas spread up to the conductor and reached it.

It is curious to note that there are also two visible steps in the luminosity which are quite sharply marked, and are also apparently sharply distinguished by their chemical action. First appears the glow, the noiseless or silent discharge. Perhaps this is the break down at some distance from the conductor, not at the conductor—while the air at the conductor still is insulating, but at some distance therefrom has broken down. This does not appear at needle points, where the break down must occur at the beginning, but it appears very markedly at plane surfaces. Then at higher voltage, the blue glow is superseded by violet streamers, which are noisy and are interrupted, intermittent, and appear to represent conduction of current, when that ionized layer of air has reached the conductor. When conduction occurs into the space, that conduction, following the gas laws, has the effect that as soon as current begins to pass locally the resistance at the space falls, a discharge occurs, the voltage disappears and the current disappears, so by the laws of gas conduction the current must be intermittent and must always be a localized expenditure of energy as a spark or streamer. At this point, apparently, the chemical action changes. Where we have the blue glow, the energy seems to be sufficient to dissociate the oxygen molecules, but not the nitrogen molecules, and ozone formation takes place. As soon as you see these violet streamers, not only the oxygen molecules, but also the nitrogen molecules split, and you get nitric-oxide, but less ozone, because at the high temperature of that streamer discharge the ozone is broken up, so that there seems to be a sharp dividing line. Below that the blue discharge produces ozone, above it the streaming discharge or brush is intermittent, and of different color, noisy, and seems able to fix nitrogen.

The whole subject is an extremely interesting one, and what I have said here I do not want to have taken as conclusive evidence, as the entire field is altogether too new to accept final conclusions. This is only my present personal opinion of what, from the evidence, appears to be probable. We must all be governed by further evidence, which may and probably will change our opinions more or less.

John B. Whitehead: Before answering the questions which have been asked in connection with my paper, I want to say a few words in general comment on the three papers which have been presented at the morning session.

These three papers all deal with the effects of high voltage on insulation. Each of the papers presents a set of experimental results on this perhaps most important of all electrical questions. All of them fail, however, to explain the observations in terms of simpler phenomena or physical laws at present understood. Nor do the few suggestions of explanations which are offered coincide either in point of view or language of expression. There is here then a sharp indication of present uncertainty surrounding these highly interesting phenomena. The uncertainty, however, is by no means as great as may appear from this confusion. The phenomenon of spark discharge in all its manifestations has been a subject of study by experimental physicists for many years. As a result of this study the ionic theory has not only paved the way for most fruitful investigation, but has been finally established as a medium through which many electrical manifestations now receive their explanations in terms of the laws of simple mechanics. For no set of phenomena is this more true than for the spark discharge in gases. While there are still many phenomena which have not yet been brought into perfect accord, those which have been studied most widely show conclusively that for a proper understanding of the conditions governing the break-down of insulation whether gaseous, liquid or solid, the way must be through the knowledge of the properties of ions which has been already gained. These comments are suggested by the mode of interpretation used by Messrs. Hayden and Steinmetz in discussing their results. We are to be congratulated upon the presentation of so careful and accurate a set of experiments in a field so little understood. The conclusions drawn from the experiments by the authors, however, invite some comment.

Disruptive discharge is said to require a definite minimum amount of energy. The laws of spark discharge in air which may be said to be firmly established, explain the phenomena in terms of motion of gaseous ions, *i.e.*, charged particles, acted on by electric force. These ions have mass, and therefore acceleration and momentum when in an electric field. The laws of motion and impact of the simple mechanical system thus presented lead in many cases to complete explanation. Spark discharge is the result of secondary ionization or the collision of a charged particle moving under electric force with a neutral molecule, thus breaking up the latter into new ions and so furnishing the conductors for the discharge. Since the free ions have mass they require time to attain speed. If the electric force is transient and of sufficiently short duration the ion may remain practically unaffected. The study then of the phenomena of transient voltages should be extended to that of the shape and duration of the voltage impulse, *i.e.*, the integrated product of intensity and time in relation to the known properties of gaseous ions. Even granting that the initial discharge voltage of the experiments is properly deduced from the ratio of turns, this value cannot exist for more than an infinitesimal time and the appendix concludes that the shortest and longest time durations of a pulse are in the ratio 1 to 100. It is concluded that the discharge does not instantly follow the application of voltage, although the observations leading to this conclusion are not described. It is also stated that during the interval energy is being supplied to the dielectric, and relations are deduced between energy and sparking distance for air and oil, as given on page 770. Although the observed points in the two cases fall on curves of different shape they are assumed to have the same equations, and although the energy is measured at the transformer primary, it is assumed to be a basis of comparison for the secondary spark-gaps. It would be interesting to know what part of the energy delivered to the magnetic circuit is regained upon opening the primary circuit. It would also be interesting if the authors would present a conception of the mechanism by which a dielectric accumulates energy leading up to disruptive discharge.

Taking up the points that were brought out in connection with my own paper, the first question was that of Mr. Mershon as to the point on the voltage wave at which the corona ceases in relation to the point at which it starts, and he raised the question as to just how you could expect the corona to stop at a lower voltage than that at which it started. The indication is that there is only a small lag, if any, in the point of disappearance of the corona. The corona, however, is a source of heat in the gas, and the raising of temperature has the effect of lowering the corona voltage.

Regarding Mr. Thomas' questions—first, the conditions at the ends of the tube: The wire is carried through a cylindrical metal bushing set in a glass receptacle of the shape very much as indicated in the drawing on page 1063. There is no observation of spark discharge, no corona nor anything else indicating ionization at this point, occurring before that on the length of wire within the tube. If you carried the wire through a rubber or other insulating bushing, ionization would first set in at that point, and would spread to some extent along the wire inside of the tube. The variation of electric field at the end of the tube is quite marked, of course, outside the tube, but does not extend to the region inside for any considerable distance. As soon as corona forms, it is very evident that no error is introduced on this account. The whole apparatus was, of course, enclosed with the idea of conducting any ionization that was generated out through the gap leading to the electrode. I think there was no error on this score.

With reference to the question as to whether in a small wire rapid change of gradient at the surface would explain any of these phenomena: The potential gradient does change very rapidly; however the distances within which the potential gradient varies widely are very much greater than mean free paths of the molecules and ions.

P. H. Thomas: You did not catch my point—the question is whether the volume of air which was subjected to something like the critical strain was not greater in the case of the large wire, not that the mean free path was involved, but the surrounding presence of supporting ionized air might prevent the overwhelming of the very narrow zone there, very narrow particles, with reference to the free paths.

J. B. Whitehead: I am not sure that I get the idea. Ionization in this case is a sharply cumulative effect. As soon as you get a region where there is this secondary ionization, when this second ionization starts, it is a continuous thing, and if you attempt to explain it by any relation between the mean free paths of the ion or the molecule, and the variation in diameter of the wire, there is the widest kind of discrepancy. I have given the figure 10^5 in the paper showing that the two quantities are of different orders of magnitude.

Referring to the question as to the state of the air as it leaves the wire, whether it has positive or negative ions—I think Mr. Lincoln asked a similar question—a gas ionized in this way has both positive and negative charges—the point of initial breakdown will be observed by charging the electroscope either positively or negatively. The only differences which come in are in the shape of the discharge curve of the electroscope. These differences are to be expected in view of the known fact of the difference in the rates at which the positive and negative ions move in the gas and the different rates at which they diffuse. The point of break-down can be observed with either kind of ion. I have not worked with any other gas than air.

The question as to the positive and negative corona is taken up in the paper, rather briefly, and I have pointed out that there is no apparent difference in the positive and negative corona unless it be possibly the somewhat greater brightness and sharper definition of one. I am not prepared to say that there was any noticeable difference.

As to the relation of initial ionization to the following arc, the corona starts evenly, as you are, of course, aware. As you go on increasing the voltage you will finally get to either a spark or an arc. Now then, just what this range of voltage is will depend on the relative diameters of the inner wire and the tube. The potential gradient between a tube and the central wire depends upon the diameter of the wire in such way that under some circumstances an increase in diameter will mean a lowering of the electric intensity and under other conditions it will mean an increase in the electric intensity. With the increase in corona diameter, resulting from increased voltage, when the corona reaches a point so that any further increase means an increase of intensity the spark or arc follows.

Dr. Kennelly and Dr. Steinmetz have each suggested that an increase due to pressure in the neighborhood of a small wire may offer a means of explaining the increase of electric intensity of corona and break-down. I am not quite sure that I grasp Dr. Steinmetz's idea, in that I cannot see why you should expect any difference between the case of small and large wires. Professor Kennelly's idea is, of course, a possible one, and there is no difficulty about imagining such a thing to occur. I would say, however, that I have made efforts to observe any increase in pressure in the neighborhood of these wires by optical means —the increased density of this air in its relation to the neighboring portions, permits the use of a very simple optical method of observation. Such experiments were negative in my case, although I cannot say I think that is any conclusive proof that some such increase of pressure may not explain the observed facts. Since we are dealing with extremely small distances, and I am not sure that even with the optical method I have used the layer would be sufficiently thick to manifest itself in this way. The test is known to physicists as the "Schlieren" method.

Professor Creighton made some comments as to the auto-ionization of the air and the necessity of removing ions. I do not know the word auto-ionization. Ions may be generated by secondary ionization, as in coronæ, and recombine very promptly; the air is then to all appearances in quite the same state as it was before secondary ionization or coronæ set in. This is shown very well by the sharpness with which the corona stops and by the absence of any after effects of ionization. There are always a certain number of free ions in the air, and these ions account for the small conductivity which air has. If you generate ions by some external means, and put them in the air, it simply means you can get a greater leakage current, but the presence of these ions does not in any way hasten or lower the point at which secondary ionization steps in, it simply increases the leakage current. There are numerous ways of removing free ions from the air; the use of glass wool, or crude raw cotton and various materials of like nature, through which the air can be drawn to a perfectly pure state, so far as ionization is concerned, but it will always have a certain extremely small number of free ions. The natural conductivity of the air is entirely explainable on this basis. For reasons which will be found in the remarks I have just made, I do not think Professor Ryan's suggestion, as well as I was able to gather it from hearing his letter read in the meeting, that there may be a difference between indoor and outdoor ionization, offers an explanation of the discrepancies that he is calling attention to. The range of natural ionization throughout the regions which have been investigated all over the earth, is about in the ratio of 1 to 4, and as I have said, the presence of more or less free ions in the air, simply increases conductivity, but I do not believe under any circumstances it would hasten the point at which secondary ionization, spark discharge, or corona would start.

Mr. Mershon has asked the effect of the wave form on the observations. The discussion of the wave form is given in the paper, showing the relation of maximum to effective values, and also in the reference to the curve Fig. 5. It is possible to observe the corona very close to the peak of the wave, and it is so sensitive that it was possible by careful voltage adjustment to pick up the three little peaks by the stroboscopic method with intervening dark spaces corresponding to the dimples.

As to Conclusion 10, that the corona has high conductivity and most of the loss takes place beyond it, that is based on the results given in the paper, where it is shown that the intensity at the edge of the corona is the same, practically the same, differing from it by a small amount, as that of a solid wire of the same diameter, and if that is the case it is a fairly reasonable assumption that the corona has high conductivity, and marks the limit at which ionization takes place.

In calling attention to Mr. Mershon's method of measurement I have been led by the process of elimination of all other explanations of the discrepancies between our results. Mr. Mershon has pointed out that his critical point is not necessarily the same as my own, but I am unable to see any other explanation than that of corona and break-down for the sharp, upward bend of his curves. I am unable to think of any means, also, by which there is a possible loss through the air below this point.

It has been suggested by several that laboratory methods present conditions different from those obtained outside and that this may be an explanation of some of these differences. I should be interested to hear some one suggest some means or method by which a loss could take place through air at voltages below those at which it actually breaks down.

M. A. de Chatelain (by letter): The writer and his associate, Professor V. F. Mitkevitch, were led to the question of corona formation and the accompanying losses in connection with the question of possibility of high-tension power transmission in the vicinity of St. Petersburg, Russia.

Laboratory experiments were performed on cylindrical conductors of different diameters, placed at different distances from each other. In view of discrepancies in the values of the critical voltage, as given by Messrs. Scott, Mershon, Ryan, Kapp, and Berg, among themselves and with our results, Professor Mitkevitch was led to investigate the matter theoretically. Based upon J. J. Thomson's researches on conductivity of gases he has found the following formula for the critical voltage:

$$E_{eff} = 35 \frac{H}{273+t} \cdot r \log_{10} \frac{d}{r} \text{ (in kilovolts)}$$

where

H is the barometric pressure in mm. of mercury;
t is the temperature of air in degrees centigrade;
r is the radius of the conductor, in cm.;
d is the distance between the centers, in cm.

Changes in humidity did not produce any appreciable variations in results. The values calculated according to the foregoing formula were checked experimentally in the electrical laboratory of St. Petersburg Polytechnic Institute, and were compared to the results given by Professors Ryan and Kapp for the same conditions. The comparison is given in Tables I and II. It will be seen that the difference between the voltages at which the corona became visible, and those calculated according to Professor Mitkevitch's formula, are not large.

It may be appropriate to mention here that Professor Kapp's adaptation of Mershon's formula (Journal of the Inst. El. Engs., February, 1910) leads to an odd result, namely, that the critical voltage, beyond a certain limit, becomes lower with increasing diameter of conductors (see Table III).

Mr. Mershon's statement that the losses increase with the frequency led us to investigate the effect of frequency. Our results seem to indicate that the loss is practically independent of the frequency, and rather decreases at higher frequencies. Namely, we measured the losses between two parallel planes, 27 x 27 cm. each, one of which was covered with needles of the same length. The distance between the points and the opposite plane was 2 cm. The frequency was varied from 15 to 90 cycles per second. After having taken into account the necessary corrections for the capacity, etc., we found the following values of losses:

Cycles	Watts
15	56
50	54.5
90	54

TABLE I

$2r$ (mm.)	d mm.	Critical kilovolts	
		Observed	Calculated*
5 (cable)	1000	65	60
11 (cable)	"	120–125	115
11 (tube)	"	125–130	115
14.3 (tube)	"	145–150	141

*Formula Professor Mitkevitch

TABLE II
CRITICAL KILOVOLTS

d mm.	$2r = 10$ mm.			$2r = 15$ mm.			$2r = 20$ mm.		
	Ryan	Kapp	Mitkevitch	Ryan	Kapp	Mitkevitch	Ryan	Kapp	Mitkevitch
500	143	82	98	180	89.5	135	212	92.5	165
1000	165	94	110	209	104	155	250	109.5	195
2000	187	106	125	236	119.5	177	287	125.5	225
3000	200	114	135	256	128	190	310	135	240

TABLE III

d mm.	$2r$ mm.									
	5	10	15	20	25	30	50	100	150	200
2000	79.3	106	119.5	125.5	128.5	131	130	119.5	—	—
10000	98	136	154	164	171	172	177	169	163	156

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VECTOR POWER IN ALTERNATING-CURRENT CIRCUITS

BY A. E. KENNELLY

It has long been known that in any simple alternating-current circuit, the current and voltage may be conveniently regarded as rotatable vector quantities.[1] It is also known that the power in such circuits is not to be regarded as the vector product of the rotating vector voltage and rotating vector current.[2] It does not seem to have been pointed out, however, that, under certain restrictions, it is proper to regard the power in an alternating-current circuit as a non-rotating vector quantity. Moreover, it does not appear to be generally known, although the fact has not escaped notice, that the imaginary component of vector power, or so-called "wattless power" is, in a restricted sense, just as much power, and just as "wattful" as the real component.[3]

The objects of this paper are:

1. To indicate the limitations under which power in an alternating-current circuit may be treated as a stationary vector;
2. To extend the technology of vector alternating-current quantities;
3. To combat the use of the terms "wattless power" and

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[1] J. A. Fleming, "Notes on Alternate Currents", "The Electrician", Nov. 18, 1887, Vol. 20, page 28.

[2] Symbolic Representation of General Alternating Waves and of Double Frequency Vector Products, by Dr. C. P. Steinmetz, TRANSACTIONS A.I.E.E., Vol. 16, pp. 269–296. June, 1899.

The use of Complex Quantities in Alternating Currents, by Geo. W. Patterson, Physical Review, Vol. 26, No. 3, Mar. 1908, pp. 266–271.

[3] The Improvement of Power Factor in Alternating-Current Systems, by Miles Walker, Journal of the Inst. of El. Engrs., Vol. 42, pp. 599–625, Jan., 1909.

" wattless current ", offering more logical terms as substitutes, and

4. To offer a plea for the standardization of the direction of phase rotation in the vectors used in alternating-current theory.

Preliminary Definitions. The vectors, or directed magnitudes, employed in alternating-current technology, with rare exceptions that do not come within the scope of this discussion, are all confined to a single plane of reference. That is to say, they relate to two dimensions of space, as distinguished from the vectors of three-dimensional geometry. This limitation may be expressed by saying that the vectors of alternating-current technology are *plane vectors*. A plane vector may be defined as a quantity having both a direction and a magnitude, but confined to one plane of reference. In what follows, we may for brevity conveniently assume that the term " vector " is an abbreviation for the more strictly logical term " plane vector ".

Subdivision of Vectors. There are three classes of vector used in dealing with alternating-current circuits, namely:

1. Vectors that are capable of rotation in their reference plane about a fixed point, and whose projections on a reference axis, or whose intercepts with polar curves, measure the instantaneous values of the quantities represented by the vectors. That is, the rotating vectors may be either *projected* or *intercepted*. These vectors may be called *rotative vectors*.

2. Vectors that are not capable of rotation in their reference plane for any purpose of projective or interceptive representation. These may be called *non-rotative vectors*.

3. Rotative-vectors that for special purposes are arrested, or treated as though non-rotative. These may be called *stationary vectors.* Stationary vectors are rotative, but non-rotating.

The above classification and nomenclature may be revealed more clearly by the following table:

TABLE I

Nomenclature and algebraic classification of alternating-current vectors.

Rotative ($l\,\underline{/\omega t}$)	....	Rotating ($l\,\underline{/\omega t}$)
	Stationary ($l\,\underline{/\omega T}$) (T = constant)	Non-rotating ($l\,\underline{/\theta}$)
Non-rotative ($l\,\underline{/\theta}$)	....	

Example of a Rotative Vector. As an example of class (1), let us consider the vector $O\,E$, Fig. 1, rotating in the plane $O\,X\,Y$, about the origin O, with a uniform angular velocity of ω radians per second. Then the length $O\,E$ may represent to an assigned

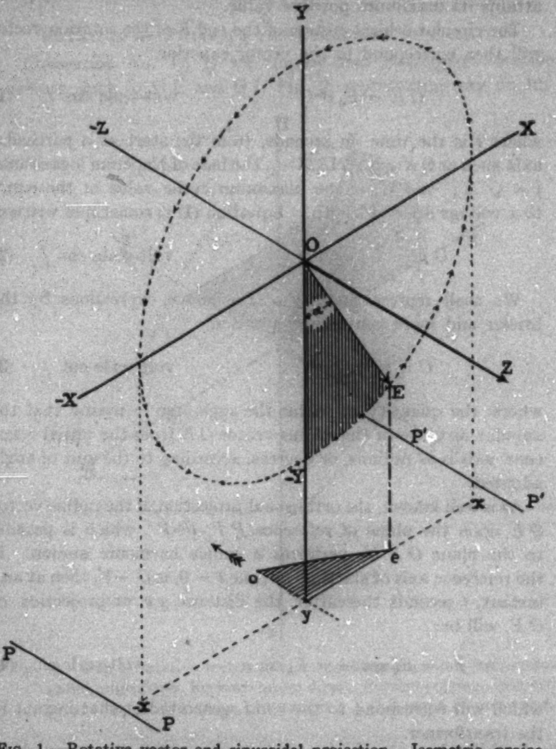

Fig. 1.—Rotative vector and sinusoidal projection. Isometric projection. $X\,O\,Y$ plane of rotation, $P\,P\,P'\,P'$ plane of projection.

scale of volts per cm., the maximum cyclic value of a certain sinusoidal e.m.f., say the e.m.f. generated harmonically in the secondary winding of a particular transformer. The direction of rotation may be positive, as indicated by the orbital arrows.

If the frequency of the voltage in the transformer is n cycles per second; then we know that the angular velocity of rotation must be $\omega = 2\pi n$ radians per second. Moreover, the vector $O\,E$ must, of course, coincide with $O\,X$ when the generated voltage attains its maximum positive value.

The circular orbital motion of the end E of the rotation vector will then correspond to the vector equation:

$$O\,E = E_0\,\varepsilon^{j\omega t} \qquad \text{volt-scale cm.}\ \underline{/\ \ } \qquad (1)$$

where t is the time, in seconds, from the start at a particular axis such as $O\,X$, ε is 2.71828..., the base of Naperian logarithms, $j = \sqrt{-1}$, and E_0 is the maximum cyclic value of the e.m.f. to a voltage scale of length. Equation (**1**) is sometimes written:

$$O\,E = E_0\,cis\,(\omega t) \qquad \text{volt-scale cm.}\ \underline{/\ \ } \qquad (2)$$

We shall represent either of the above expressions by the briefer and more convenient notation:

$$O\,E = E_0\,\underline{/\omega t} \qquad \text{volt-scale cm.}\ \underline{/\ \ } \qquad (3)$$

where the quantity ωt within the angle sign $\underline{/\ \ }$ means that the angular distance of the radius vector $O\,E$ from the initial reference axis is ωt radians, or degrees, according to the unit of angle adopted.

As is well known, the orthogonal projection of the radius vector $O\,E$ upon the plane of reference $P\,P$, $P'\,P'$, which is parallel to the plane $O\,X\,Y$, performs a simple harmonic motion. If the reference axis of starting, at time $t = 0$, is $O\ -Y$, then at any instant, t seconds thereafter, the distance $y\,e$, or projection of $O\,E$, will be:

$$\overline{y\,e} = E_0 \sin \omega t = E_0 \sin \alpha \qquad \text{volt-scale cm.} \qquad (4)$$

which will correspond to the e.m.f. generated at that instant in the transformer.

Again, if the reference axis of starting, at time $t = 0$, is $O\,X$, then at any time t:

$$\overline{y\,e} = E_0 \cos \omega t = E_0 \cos \alpha \qquad \text{volt-scale cm.} \qquad (5)$$

If the plane of projection $P\,P\,P'\,P'$ be moved parallel to itself in the direction shown by the arrow at o; or, if with the plane of projection at rest, the coördinate system of axes moves in the direction $O Z$, with uniform linear velocity, then, as is well known, the projecting point will trace out a sinusoid $o e$ having amplitude ordinates $o x$, and time abscissas $o y$.

RELATION OF PHASE TO THE DIRECTION OF ROTATION

Convention No. 1. If we employ two co-frequent rotative vectors, such as $O E$ and $O I$, Fig. 2, representing say an impressed e.m.f., to a certain volt-scale, in a simple alternating-current circuit, and the current strength thereby produced in the same circuit, to a certain ampere-scale; then, if there is inductive reactance in the circuit, we know that the current will lag behind the impressed e.m.f. This means that the orthogonal projection of $O I$ on the axis $O X$ of reference, must reach its maximum after $O E$ has passed its maximum projection on that

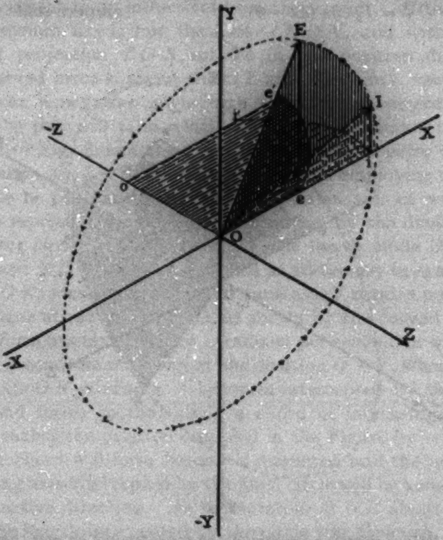

FIG. 2.—Pair of rotative vectors of the same frequency and their cosinusoidal projections. Representation direct. Current lagging. Isometric projection. $X O Y$ plane of rotation. $X O Z$ plane of projection.

axis. Consequently, with the plane $X\,O\,Z$, fixed in space, and with the vectors $O\,E$, $O\,I$, rotating in the positive direction, as shown by the orbital arrows, $O\,I$ must make a negative angle with $O\,E$; or, $O\,E$ must make a positive angle with $O\,I$; so that the angle $E\,O\,I$ is trigonometrically *negative*, as shown in Fig. 2. If the vector $O\,E$ starts from the position $O\,X$, at time $t = 0$, the orthogonal projection of $O\,I\ \underline{/\omega t - \theta}$ proceeds to execute on the axis $O\,X$ the cosinusoid:

$$\overline{O\,i} = I_0 \cos(\omega t - \theta) \qquad \text{ampere-scale cm.} \qquad (6)$$

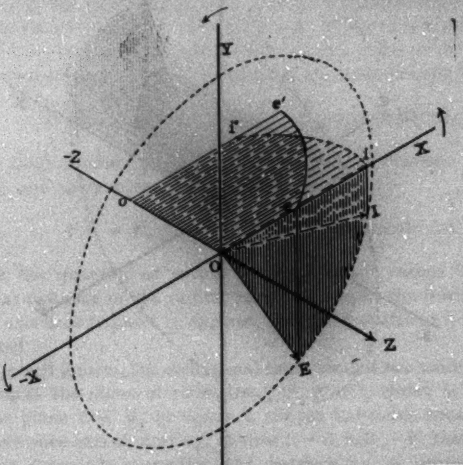

Fig. 3.—Pair of rotative vectors of the same frequency and their cosinusoidal projections. Representation inverse. Current lagging. Isometric projection. $X\,O\,Y$ plane of rotation. $X\,O\,Z$ plane of rotation.

If the origin O and system of axes advance uniformly with respect to the stationary plane of projection $X\,O\,Z$ in the direction $O\,Z$; or, what is equivalent, if the plane of projection moves in the direction $O\,Z$ past a fixed origin O, the cosinusoids $e'\,e$ and $i'\,i$ will be traced as curves with amplitude ordinates, and times as abscissas. This convention was adopted in alternating-current technology by Fleming in 1887.[1]

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[1] Fleming, loc. cit.

Convention No. 2. If, however, we reverse the direction of rotation of the vectors $O\,E$, $O\,I$ in their orbit; *i.e.*, if we adopt negative rotation, we shall require that the leading vector make a negative angle with the lagging vector, a condition opposite to that above defined.[2] Or, keeping the direction of rotation positive, we may assume that the vectors are fixed in their plane; but that the plane of projection rotates positively at the uniform angular velocity ω. Thus in Fig. 3, the two vectors $O\,E$ and $O\,I$ may respectively represent, as before, the impressed e.m.f. and the current in an inductively reactive circuit. If these two vectors remain fixed; but the axis $-X\,O\,X$, and with it the plane of projection $Z\,O\,X$, rotates in the positive direction, of the curved arrows, about the $O\,Z$ axis, the e.m.f. vector $O\,E$ must make a negative angle with the lagging current vector $O\,I$; or the pair will take relatively opposite positions to those they had in Fig. 2, and the angle $E\,O\,I$ will be *positive.*

Convention No. 3. Some writers, instead of employing rotative vectors to be projected orthogonally upon an axis of reference, prefer to represent simple harmonic motion by the device of an *intercepting circle.*[3] Thus, in Fig. 4, the heavy circle $O\,G\,E\,F$, in the plane $X\,O\,Y$, may be regarded as stationary in space, and the axis $O\,R$, sometimes called a "time-axis," rotates positively in this plane about the origin O, as shown by the curved arrows, with uniform angular velocity ω radians per second, or n revolutions per second, commencing at the position $O\ -Y$, when $t = 0$. As the axis $O\,R$ advances, it becomes intercepted by the circle $O\,G\,E$, and forms to that circle a chord of increasing length, until it reaches the position occupied in the Figure by $-X\,O\,X$, when the chord will have become a diameter, and the length of the moving axis intercepted by the fixed circle will be a maximum in the positive direction. As the rotation of $O\,R$ about O continues, the length intercepted by the circle will diminish, until it will be zero in the position $O\,Y$. Continuing the rotation, we may adopt either of two equivalent conventions, between which writers are divided. We may either use a second circle, shown in dotted lines at $O\,g\,e\,f$, equal and opposite to the first, and consider this to be a negative circle, such that all intercepts upon

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[2] Gisbert Kapp, "Alternate-Current Machinery", Fig. 7, Proc. Civil Engineers, London, 1889, reprinted in Van Nostrand Science Series, New York, 1889, p. 27.

[3] Kapp, loc. cit., Fig. 8.

C. P. Steinmetz, "Alternating-Current Phenomena", 1897.

$O\,R$ shall be considered negative, intercepts on $O\,r$ being ignored; or, we may dispense with the second circle, and allow intercepts on $O\,r$ to count as negative intercepts, during the second half of the revolution. In either case, the length of the intercept on the moving axis will follow a simple harmonic law, according to the expression $O\,E \sin \omega t$ units of length, $O\,E$ being the diameter of the intercepting circle.

If the rotating axis starts, at time $t = 0$, from the position $-X\,O\,X$ in Fig. 4, the length intercepted by the fixed circle will likewise follow a simple harmonic law according to the expression $O\,E \cos \omega t$.

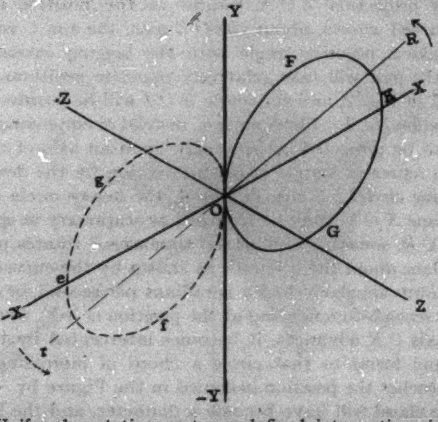

FIG. 4.—Uniformly rotating vector and fixed intercepting circle, with simple harmonic intercept. Isometric projection. $X\,O\,Y$ plane of rotation.

In order to represent the relation between a simple harmonic current in an inductively reactive circuit under a simple harmonic e.m.f. by convention 3, two intercepting circles are required, as in Fig. 5. Here the negative counterparts are omitted, and negative intercepts are assumed with each circle. As shown in the figure, it is necessary, with the positive direction of rotation of the moving axis $O\,R$, to have the diameter of the circle $O\,I$ make a positive angle with the diameter of the circle $O\,E$, in order that the intercept on the current circle shall reach its maximum later than the intercept on the voltage circle. A lagging current, therefore, requires a *positive* angle $E\,O\,I$.

In the practical use of convention 3, the circles are commonly omitted, for convenience, and are merely represented by their diameters *O E* and *O I*, which become respectively the stationary-vector e.m.f. and current of the diagram.

As regards the use or disuse of the negative circle, as in Fig. 4, it is simpler to dispense with it, and to use negative intercepts on *O Y*, except when the positive and negative waves are not symmetrical. In that case, the retention of the negative loop simplifies the diagram, since it avoids superposition of loops, and ambiguity of paths.

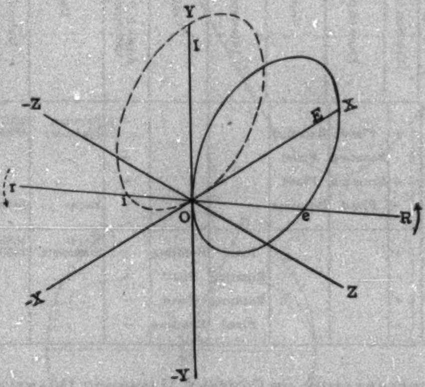

Fig. 5.—Pair of intercepting circles representing a simple harmonic e.m.f. and a simple harmonic current lagging 90 deg. behind the same. Isometric projection. *X O Y* plane of rotation. Representation inverse.

Convention No. 4. If we assume that the axes of Fig. 5 are fixed in space, but that the intercepting circles *O E* and *O I* rotate together in the positive direction about the center *O*, measuring off from moment to moment intercepts on some axis, say *O X*, equal to the respective instantaneous voltage and current; then in order to represent an e.m.f. and a lagging current, it will be necessary for the diameter of *O E* to make a positive angle *I O E* with the diameter of *O I*, or the angle *E O I* will be *negative*, the opposite condition to that in Fig. 5. According then to convention 4, Fig. 5 would represent a current *O I* leading the e.m.f. *O E* by 90 degrees.[1]

Convention No. 4 does not seem to be in use, but is introduced here in order to complete the classification symmetrically, see Table II.

TABLE II

Conventions Employed in Rotative - Vector Diagrams

Convention		Direction of rotation	Plane of projection	Vectors	Intercepting circles	Vector	Angle *E O I* for an inductive circuit	User	Date of use	Expression of inductive impedance	Representation
Type	No.										
Orthogonal projection or clock diagram	1	+	Fixed	Rotating			−	Fleming Blakesley	1887 1889	$r + j x$	Direct
		-	Rotating	Fixed			−	...		$r + j x$	
	2	+	Rotating	Fixed			+	...		$r - j x$	Inverse
		−	Fixed	Rotating			+	Kapp	1889	$r - j x$	
Polarcoördinates or Intercepting circles	3	+			Fixed	Rotating	+	Kapp Steinmetz	1889 1893	$r - j x$	Inverse
		-			Rotating	Fixed	+	...		$r - j x$	
	4	+			Rotating	Fixed	−	...		$r + j x$	Direct
		-			Fixed	Rotating	−	...		$r + j x$	

REPRESENTATION OF COMPLEX HARMONIC QUANTITIES

It has been claimed that a complex harmonic quantity is only capable of being represented as a closed curve to polar coördinates by the method of the intercepting curve, and that the projecting curve, or "clock-diagram", cannot be used in such cases.[1] It is true that the simple projecting-circle or clock-diagram, with uniform angular velocity of the radius vector, cannot represent a non-sinusoidal or complex harmonic wave; just as it is true that the simple intercepting circle, with uniform angular velocity of the radius vector, cannot represent a complex harmonic wave. But in the same manner that a change in the form of intercepting curve will permit of any complex wave being presented in polar coördinates, so a corresponding change in the form of the projecting curve will permit of the same result. Thus in Fig. 6, the sinusoid *A B C D*, drawn to rectangular coördinates, may be represented either by the projecting circle

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[1] The above four conventions by no means exhaust the possibilities of rotative-vector representation. For example, as a subtype of interceptive or polar representation, we might assume the two circles *O E*, *O I* of Fig. 5 to have their diameters on one and the same line, instead of being angularly displaced. Two angularly rotating displaced vectors could then be employed for e.m.f. and current intercepts respectively, instead of the single rotating vector *O R*. With such an arrangement, a lagging vector current *O I* would make a negative angle with the e.m.f. vector *O E*, or would reverse the relations of Fig. 5. That is, it would produce direct representation. Since, however, this method does not seem to have been used, it is omitted from the Classified Table of Conventions.

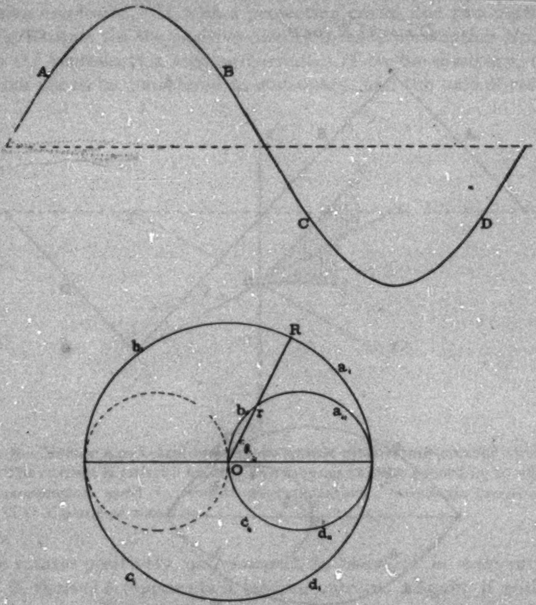

FIG. 6.—Sinusoidal wave and its projecting circle and its intercepting circle.

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[1] Alternating-Current Phenomena, by C. P. Steinmetz, 4th Edition, 1908, p. 44.

$a_{,}\ b_{,}\ c_{,}\ d_{,}$, or by the intercepting circle $a_{,,}\ b_{,,}\ c_{,,}\ d_{,,}$, with or without its dotted neighbor. Similarly, in Fig. 7, the triangular wave *A B C D*, drawn to rectangular co-ordinates, may be represented either by the projecting curve $a_{,}\ b_{,}\ c_{,}\ d_{,}$, or by the intercepting curve $a_{,,}\ b_{,,}\ r\ O$, with or without its dotted neighbor. The relation between corresponding radii on the polar curves is always:

$$\overline{O r} = \overline{O R} \cos \theta \qquad \text{cm.} \quad (7)$$

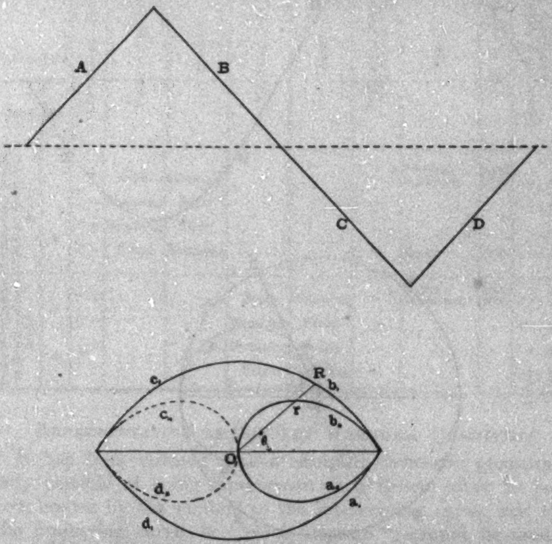

Fig. 7.—Triangular wave, its projecting curve, and its intercepting curve.

where $\overline{O r}$ is the radius vector (Figs. 6 and 7) of the intersecting curve, at the angle θ with the initial line of reference, and $\overline{O R}$ is the corresponding radius vector of the projecting curve. Consequently, having given either the polar projecting curve, or the polar intercepting curve of any complex harmonic alternating-current wave, the other can be immediately deduced.

It will be evident from the above considerations that with a pair of rotative vectors (Fig. 8) in the plane *X O Y*, one *O E* representing an impressed e.m.f., and the other *O I* the resulting current, in a simple alternating-current circuit, the question as to whether *O I* is to be interpreted as a leading or a lagging current does not depend upon the use of projecting as against intercepting curves. It may be either a leading or a lagging current with either the " clock " diagram (Fig. 1) or the " spectacles " diagram (Fig. 4). It depends entirely upon the convention employed. If, with a projecting curve, the two vectors of Fig. 8 rotate (in the positive direction) as in convention No. 1, then *O I* represents a lagging current. If on the contrary, the vectors are to be considered as stationary, and the axis of reference rotates positively with respect to them, as in convention No. 2, then *O I* represents a leading current. Again, if with a fixed intersecting axis *O X*, a pair of circles located with their rotating diameters on *O E* and *O I*, the vectors of Fig. 8 rotate in the positive direction, as in convention No. 4, *O I* represents a lagging current. Finally, if the vectors *O E* and *O I* are fixed, and represent the diameters of fixed intersecting circles, with respect to which an axis of reference rotates positively, as in convention No. 3, *O I* represents a leading current.

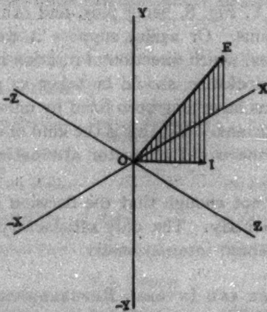

Fig. 8.—Vector e.m.f. and current in simple alternating-current circuit. The current is either a leading or a lagging current according to which convention used in vector representation. Isometric projection. *X O Y* plane of rotation.

Aside from mental habit and psychological inertia, any one of these conventions appears to be as good as another. If the positive direction of rotation is understood in all cases, each convention appears to be logical and systematic. It cannot be maintained that one or more are right and the rest are wrong. The question is essentially one of arbitrary convention, not of demonstration. Nevertheless, it is very important that the matter should be settled definitely by general agreement.[1] Much ambiguity results from the present dissension; because it is often difficult to ascertain, when opening a text-book in order to consult it, which method of representation the author follows. Imagine the confusion which would ensue in the worlds of pure and applied mathematics, if it were left to the choice of each writer to select which direction of the axis $-X\,O\,X$ Fig. 8, say, should be positive; so that some books should be written on the assumption of $O\,X$, Fig. 8, being plus, and others on the basis of $O\,X$ being minus. Or again, suppose it were left open to individual selection, which direction of rotation in a plane, clockwise, or counter-clockwise, should be taken as positive. These arbitrary selections have long been fixed by universal agreement among mathematicians. Yet this is the kind of dissension which exists to-day in the world of vector alternating-current technology.[1]

Moreover, it is not enough that the decision should be made and accepted nationally. The only satisfactory decision must be made and accepted internationally.

DIRECT AND INVERSE REPRESENTATION

In what follows, this paper will conform to what seems the majority of opinion on this matter, and $O\,I$ in Figs. 8 and 10, will be regarded as a lagging current with respect to the e.m.f. $O\,E$. This means adhering to conventions 1 and 4, and by preference to convention 1. This method of representation which, in the direction of positive rotation, makes a *leading* current *lead*, and a *lagging* current *lag*, with respect to its e.m.f., will be called, for the purposes of distinction, *direct representation*, and the opposite method, involving either convention 2 or convention 3, will be called *inverse representation*.

Tables III and IV contain lists, which are by no means exhaustive, of publications using direct and inverse representations respectively. No attempt has been made to discover more publications using one method than the other, and in the search that led to the formulation of these lists, no publications which contained vector diagrams were discarded, except such as made it difficult to decide which method was followed. The fact that 42 publications appear in the list of direct representation and 24 in the list of inverse representation, indicates a distinct preponderance in favor of direct representation. The dissension is not confined to any single country, or group of countries, and it dates as far back as 1889 at least.

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[1] The urgent need for the standardization of alternating-current vector rotation has been pointed out by various writers, both in this country and in Europe. See W. S. Franklin: A discussion of some points in Alternating-Current Theory. TRANSACTIONS A.I.E.E., May 1903, Vol. 21, pp. 589–601, and Carl Richter, Alternating-current Diagrams, Elek. u. Maschinenbau, July 12, 1908, pp. 608, 609.

TABLE III

PUBLICATIONS EMPLOYING DIRECT REPRESENTATION OF ALTERNATING-CURRENT VECTORS

Name of publication	Author	Publisher	Date
1. Conductors for Electrical Distribution.	F. A. C. Perrine	D. Van Nostrand, N. Y.	1907
2. Electrical Engineer's Pocket Book	H. A. Foster	"	1908
3. Alternating-Current Machines.	Sheldon, Mason and Hausmann	"	1909
4. Standard Handbook for Electrical Engineers		McGraw Pub. Co., N. Y.	1908
5. Munroe & Jamieson's Pocket Book		Ch. Griffin & Co., London	1908
6. Direct and Alternating Current Testing	F. Bedell	D. Van Nostrand, N. Y.	1909
7. Elements of Electrical Engineering	Franklin & Esty	MacMillan Co.	1909
8. Electric Waves	W. S. Franklin	"	1909
9. Standard Polyphase Systems	M. A. Oudin	D. Van Nostrand	1909
10. The A. C. Transformer	F. G. Baum	McGraw Pub. Co.	1903
11. Electric Power Transmission	L. Bell	"	1907
12. Problems in Electrical Engineering	W. V. Lyon	"	1908
13. Electrical Engineering Leaflets	Houston & Kennelly	The Elec. Engineer	1897
14. A Laboratory Manual of Physics and App. El.	E. L. Nichols	MacMillan Co.	1894
15. Alternating Currents	Bedell & Crehore	W. J. Johnston Co.	1893
16. Alternating Currents	D. C. & J. P. Jackson	MacMillan Co.	1896
17. Electrical Transmission of Energy	A. V. Abbott	D. Van Nostrand	1904
18. Alternating-Current Motors	A. S. McAllister	McGraw Pub. Co.	1907
19. The Elements of Alternating Currents	Franklin & Williamson	MacMillan Co.	1901
20. Alternating-Current Machinery	W. Esty	Am. Sch. Corresp.	1909
21. Electrical Measurements	Carhart & Patterson	Allyn & Bacon	1895
22. A Text Book of Electrical Machinery	Ryan, Norris and Hoxie	John Wiley	1903
23. The Principles of A. C. Working	A. Hay	Biggs & Co.	1897
24. Telephone Lines and their Properties	W. J. Hopkins	Longmans Green	1894
25. Experimental Electrical Engineering	V. Karapetoff	John Wiley	1908
26. Electrical Problems	Hooper & Wells	Ginn & Co.	1902
27. The Dynamo	Hawkins & Wallis	MacMillan Co.	1909
28. Electricity and Magnetism	F. E. Nipher	J. L. Boland Co.	1895

Name of publication	Author	Publisher	Date
29. Alternating Currents	C. G. Lamb	Ed. Arnold, London	1906
30. Lecons d'Electrotechnique Générale	P. Janet	Gauthier-Villars	1908
31. Pratique Industrielle des Courants Alt:	G. Chevrier	Carré & Naud	1900
32. Recherche Elémentaire des Relations:	O. de Bast	Léon de Thier	1899
33. Distribution de l'Energie par Courants Polyphases	J. Rodet	Gauthier-Villars	1903
34. La Technique de la Houille Blanche	E. Pacoret	Dunod et Pinat	1908
35. Moteurs Synchrones	A. Blondel	Gauthier-Villars	—
36. Die Wissenschaftlichen Grundlagen der Elek:	G. Benischke	J. Springer	1907
37. Fernleitung von Wechselströmen	G. Roessler	J. Springer	1905
38. Handbuch der Elektrischen Beleuchtung	Herzog & Feldmann	"	1907
39. Messungen an Elektrischen Maschinen	R. Krause	"	1907
40. Ein-und Mehrphasen W: Erzeuger	F. Niethammer	Hirzel	1900
41. Der Drehstrom	J. Krämer	H. Costenoble	1896
42. La Tecnica delle Correnti Alternate	G. Sartori	Ulrico Hoepli	1903

TABLE IV

PUBLICATIONS EMPLOYING INVERSE REPRESENTATION OF ALTERNATING-CURRENT VECTORS

Name of Publication	Author	Publisher	Date
1. Dynamo-Electric Machinery	S. P. Thompson	Spon & Chamberlain	1905
2. Elements of Electrical Engineering	C. P. Steinmetz	El. W. & Engr.	1902
3. Electrical Energy	E. J. Berg	McGraw Pub. Co.	1908
4. Whittaker's El. Engr's. Pocket Book		Whittaker & Co.	1906
5. Electrical Engineering	Thomälin	Longmans Green	1907
6. Electrical Engineering	Rosenberg, Gee & Kinzbrunner	John Wiley	1908
7. The Induction Motor	B. A. Behrend	El. W. & Engr.	1901
8. Transformers	Gisbert Kapp	Whittaker & Co.	1908
9. Vectors and Vector Diagrams	Cramp & Smith	Longmans Green	1909
10. Alternating-Current Engineering	E. B. Raymond	D. Van Nostrand	1907
11. Polyphase Currents	A. Still	Whittaker & Co.	1906
12. Practical Calculation of Transmission Lines	L. W. Rosenthal	McGraw Pub. Co.	1909
13. Electrical & Magnetic Calculations	A. A. Atkinson	D. Van Nostrand	1903
14. Laboratory & Factory Tests in El: Engg:	Sever & Townsend	"	1907
15. Electricity and Magnetism	Foster & Atkinson	Longmans Green	1896
16. Electric Motors	H. M. Hobart	Whittaker & Co.	1904
17. Single-phase Commutator Motors.	F. Punga	"	1906
18. Essais des Machines	Duquesne et Rouviére	Béranger	—
19. Stromverteilungssysteme	P. Häfner	Jänecke	1906
20. Untersuchung elektrischer Systeme.	H. Hausrath	J. Springer	1907
21. Der Drehstrommotor	J. Heubach	J. Springer	1903
22. Die Wechselstromtechnik	E. Arnold	"	1902
23. Ruhende Umformer	V. Bondi	Jänecke	1908
24. Impianti Elettrici a Correnti Alternate	A. Marro	V. Hoepli	1907

EXAMPLE OF A NON-ROTATIVE VECTOR

A simple example of a non-rotative vector is an ordinary impedance of the type $z\,\underline{/\theta}$ ohms, as indicated in Fig. 9. An ordinary impedance does not pass through zero cyclically, like an alternating e.m.f. or current, and no practical use is at present derivable from the notion of rotating a vector impedance about its origin. In direct representation, the impedance of Fig. 9 is essentially an inductive impedance, as distinguished from a condensive impedance. That is, it represents the impedance of some particular reactance coil. With inverse representation, however, it would necessarily represent a condensive impedance, or the impedance of some particular condenser, operated at a certain frequency, in series with a certain resistance.

Impedances, admittances, reluctances and permeances, when treated as vectors, are essentially non-rotative vectors.

Quantitatively, the application of a non-rotative vector to a rotative vector as a multiplying factor alters both the magnitude and the phase of the resultant rotative vector, without altering the frequency or angular velocity of rotation. Thus the relation:

$$I\,\underline{/\omega t} \times Z\,\underline{/\theta} = I\,Z\,\underline{/\omega t + \theta} \quad \text{volts } \underline{/\;} \qquad (8)$$

indicates that the product of a vector current I amperes, rotating with the angular velocity ω radians per second, and a vector impedance of Z ohms, with the fixed angle θ radians, gives rise to a vector voltage $I\,Z$, rotating with the same angular velocity as I, but advanced θ radians in phase beyond I. The orthogonal projection of the voltage product will follow a simple harmonic motion, θ radians advanced in phase with respect to the corresponding motion of I.

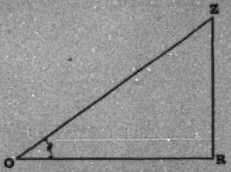

FIG. 9.—Non-rotative vector inductive impedance. Direct representation.

DEGRADATION OF A ROTATIVE VECTOR INTO A STATIONARY VECTOR

It frequently happens that a quantity which is capable of being regarded as a rotative-vector quantity, needs only to be designated as a vector in respect of phase relation to another vector or vectors; as, for example, when a simple harmonic alternating current, of say 10 amperes r.m.s., is desired to be designated as a vector lagging, perhaps 37 degrees in phase, behind a simple harmonic impressed e.m.f. of 100 volts r.m.s. It would be possible to give a direct representation of this condition as in Fig 2 with a rotative vector OE of 141.4 volt-scale length, followed at 37 deg. by a rotative vector OI of 14.14 ampere-scale length. But if there is no necessity for drawing attention to the orthogonally projective properties of these vectors, they may be represented as a simple non-rotative pair, OE, OI, Fig. 10, in which case it is convenient to use their virtual or root-mean-square values, instead of their maximum values. We may consider that, quantitatively, this diagram represents the following conditions:

$$OE = OI\,\underline{/0^\circ} \times Z\,\underline{/37^\circ} \qquad \text{volt-scale cm.}\ \underline{/\quad} \qquad (9)$$

and

$$OI = OE\,\underline{/0^\circ} \div Z\,\underline{/37^\circ} \qquad \text{ampere-scale cm.}\ \underline{/\quad} \qquad (10)$$

That is, there is some non-rotative vector impedance of $10\,\underline{/37^\circ}$ ohms which connects, by Ohm's law, a virtual e.m.f. of 100 volts with a virtual current of 10 amperes lagging 37 deg. behind it.

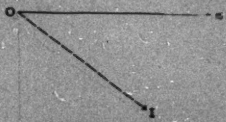

FIG. 10.—E.m.f. and lagging current. Stationary vectors.

In general, therefore, a non-rotative vector operator, such as an impedance, multiplied into a rotative vector, produces a rotative vector of changed amplitude and phase, but when multiplied either into a pure non-rotative vector, or into a stationary vector, produces a non-rotating vector of changed amplitude and phase, according to the property of multiplication of complex numbers:

$$a\,\underline{/\alpha} \times b\,\underline{/\beta} = a\,b\,\underline{/\alpha+\beta} \qquad \text{numeric}\ \underline{/\quad} \qquad (11)$$

POWER IN SIMPLE ALTERNATING-CURRENT CIRCUITS

It is well known that if a simple harmonic e.m.f. $E_0 \cos \omega t$ volts, where E_0 is the maximum cyclic value, propels a simple harmonic current $I_0 \cos (\omega t \pm \theta)$ amperes; so that the e.m.f. and current differ in phase by the positive or negative angle θ, the electric power developed in the circuit by the source of e.m.f. on the current is at any instant:

$$p_t = \frac{E_0 I_0}{2} \{\cos \theta + \cos (2\omega t \pm \theta)\} \qquad \text{watts} \qquad (12)$$

$$= E I \{\cos \theta + \cos (2\omega t \pm \theta)\} \qquad " \qquad (13)$$

where E and I are respectively the virtual or root-mean-square e.m.f. and current; or if P be the product $E\,I$, of root-mean-square volts and amperes:

$$p_t = P\,\{\cos\theta + \cos(2\omega t \pm \theta)\} \qquad \text{watts} \quad \textbf{(14)}$$

Consequently, any projective or interceptive rotating vector which represents the power in a simple alternating-current circuit must possess an angular velocity double that of the e.m.f. or current. Moreover the origin or axis of the rotating vector power must be displaced from the origin of the e.m.f. and current components.

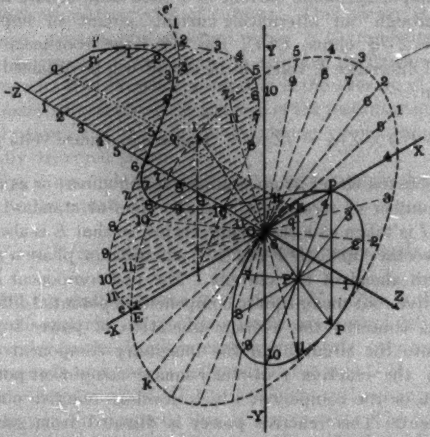

FIG. 11.—Rotative vector e.m.f. and current in inductively impedant circuit with double-frequency rotative vector power. Power factor 0.5. Isometric projection. Direct representation. $X\,O\,Y$ plane of rotation, $X\,O\,Z$ plane of projection.

It has been pointed out by Mr. J. Irving Brewer[1] that a construction which satisfies the rotative-vector power relations is to lay off $O\,E$, the maximum cyclic e.m.f., along the $O\,X$ axis, (Fig. 11) and $O\,I$ at the proper phase angle; in the case presented,

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[1] "Electrical World" Jan. 21, 1909, Vol. 53, No. 4, pp. 217–218. Inverse Notation.

$X\,O\,P$. Then on $O\,P$ at a point P', such that $O\,P' = E\,I$, to watt-scale, is the center of the rotating power vector which starts with doubled angular velocity from the position $P'\,P$, at the moment when E_0 starts from $O\,X$, and I_0 from $O\,P$.

Under these conditions, the three rotating vectors will project on the fixed axis $-X\,O\,X$, and on the moving plane $X\,O\,Z$, the respective instantaneous values of power, e.m.f. and current.

NON-ROTATIVE VECTOR POWER

If a simple harmonic current of I root-mean-square amperes flows through an alternating-current circuit of impedance $R + j\,X = Z\,\underline{/\alpha}$ ohms, ($A\,C$, Fig. 12), the root-mean-square potential-difference E volts on the circuit will be obtained by the operation:

$$E\underline{/\alpha} = I\underline{/0} \times Z\underline{/\alpha} = IZ\underline{/\alpha} \qquad \text{root-mean-square volts } \underline{/\quad} \qquad (15)$$

Here I is taken either as an ordinary real number, or as a plane vector number of zero angle, and therefore at standard phase. That is, I is taken as a stationary vector, so that E is also a stationary vector e.m.f., ($D\,F$ Fig. 12), advanced in phase α radians or degrees ahead of the current. The real component $D\,E$, is the effective root-mean-square component of potential difference, so far as concerns the average liberation of power from the source into the circuit, and the imaginary component $E\,F = j\,I\,X$, is the reactive root-mean-square component potential-difference, or the component which develops reactive power on the current. This reactive power is directed from source to circuit, and back again, in one power cycle, or in one half-cycle of current.

Again, if we multiply the non-rotative vector p.d. $D\,F$ by the stationary, vector current, according to the formula:

$$P\underline{/\alpha} = I\underline{/0} \times E\underline{/\alpha} = I\,E\underline{/\alpha} = E\,I\underline{/\alpha} \qquad \text{watts}\underline{/\quad} \qquad (16)$$

we obtain a stationary vector power G K, advanced α degrees or radians ahead of the current. This power is the apparent power, commonly called volt-amperes. It is perhaps practically advantageous to call the unit of apparent power the volt-ampere in order to distinguish apparent power from effective power in engineering; but a volt-ampere is essentially a watt, and the apparent power is correctly stated as apparent or resultant watts, the vector sum of effective and reactive watts[1]. The effective component *G H* is the average power delivered to the circuit by the generator, and is usually called the " real power ". The reactive power *H K* is, however, when considered from within the circuit, just as real as the effective power *G H*; so that the term " real power " is unsuitable. The reactive power *H K* is the maximum cyclic power expended in transmitting energy into and out of the magnetic flux linked with the circuit, being alternately plus and minus, or from and to the generator, in successive quarter cycles of current. This energy is kept in the circuit; whereas the effective power *H G* transmits energy out of the circuit. The maximum reactive cyclic power *H K* is all internal. The effective power *G H* is the average of that delivered externally, is the cyclic average of the instantaneous total internal power, and is also the maximum cyclic value of the externally delivered power.

Finally, if we divide the stationary vector power by 2ω according to the equation:

$$W\underline{/\alpha} = P\underline{/\alpha}\ /\ (2\omega) \qquad \text{joules per energy cycle } \underline{/\ \ } \qquad \textbf{(17)}$$

we obtain the stationary energy vector *L N*. This is the maximum cyclic apparent, or resultant oscillatory, energy delivered by the generator to the circuit in each energy cycle, over and above the average effective energy delivered at the rate *G H*. The perpendicular component *M N* is the maximum cyclic change of reactive energy in the magnetic flux of the circuit. The horizontal component *L M* is the maximum cyclic oscillation of effective energy.

A practical example will illustrate the above conditions. We may assume a large single-phase 60-cycle alternator delivering at its switchboard eight megawatts (8,000 kw.) of effective power, and three megawatts of reactive power, or 8.544 apparent megawatts, under a power factor of 0.936. If the delivered current is 4,000 amperes, its terminal voltage will be 2,136 volts.

The stationary-vector power diagram for this generator is shown at *G H K* in Fig. 12. The analysis of the circuit conditions is given in Fig. 13, to rectangular coördinates and to sinusoidal current phase. The current I has a maximum cyclic strength of $4000\sqrt{2}$, or 5,656 amperes. The potential difference E is ahead of the current by $\alpha = 20.6$ deg. It is analyzed into the effective component ($D\,E$ Fig. 12) of 2,000 volts root-mean-square, or $E_f = 2{,}828$ volts maximum (Fig. 13)

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[1] A useful diagram of this type—essentially a stationary-vector power diagram—appears at page 540 of Mr. Percy H. Thomas' paper on " Calculation of the High-Tension Line ". PROCEEDINGS of A.I.E.E., June, 1909.

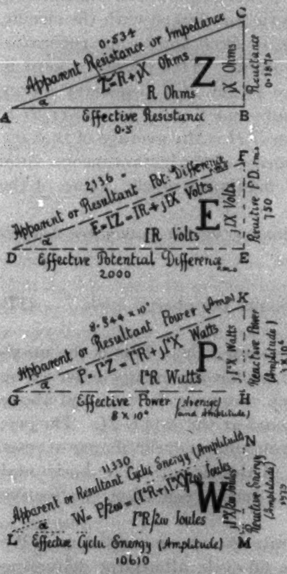
C
0·534
Apparent Resistance or Impedance
Z = R + jX Ohms
Z
jX Ohms
Reactance
0·187
R Ohms
α
A
Effective Resistance
0·5
B
F
2136
Apparent or Resultant Pot: Difference r.m.s.
E = IZ = IR + jIX Volts
E
jIX Volts
Reactive P.D. r.m.s.
750
IR Volts
α
D
Effective Potential Difference r.m.s.
2000
E
K
8·544 × 10⁶
Apparent or Resultant Power (Amp)
P = I²Z = I²R + jI²X Watts
P
jI²X Watts
Reactive Power (Amplitude)
3 × 10⁶
I²R Watts
α
G
Effective Power (Average and Amplitude)
8 × 10⁶
H
N
11330
Apparent or Resultant Cyclic Energy (Amplitude)
W = P/2ω = (I²R + jI²X)/2ω Joules
W
jI²X/2ω Joules
Reactive Energy (Amplitude)
3979
I²R/2ω Joules
α
L
Effective Cyclic Energy (Amplitude)
10610
M

FIG. 12.—Stationary vector diagrams of impedance, potential-difference, power and cyclic energy in an alternating-current circuit to phase of current as standard.

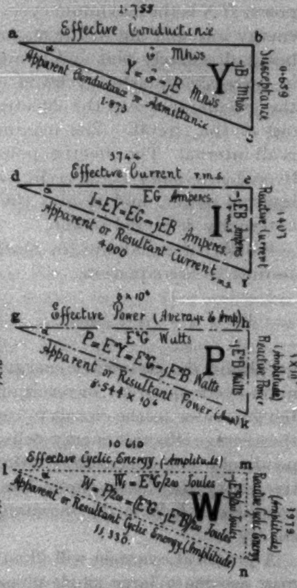
1·755
a
Effective Conductance
b
α
g Mhos
Y = g − jB Mhos
Y
−jB Mhos
Susceptance
0·659
Apparent Conductance or Admittance
1·873
c
3744
d
Effective Current r.m.s.
e
α
EG Amperes
I = EY = EG − jEB Amperes
I
−jEB Amperes r.m.s.
Reactive Current
1407
Apparent or Resultant Current r.m.s.
4000
f
8 × 10⁶
g
Effective Power (Average & Amp)
h
α
E²G Watts
P = E²Y = E²G − jE²B Watts
P
−jE²B Watts
Reactive Power (Amplitude)
3 × 10⁶
Apparent or Resultant Power (Amp)
8·544 × 10⁶
k
10 610
Effective Cyclic Energy (Amplitude)
l
m
α
W_f = E²G/2ω Joules
W = P/2ω = (E²G − jE²B)/2ω Joules
W
−jE²B/2ω Joules
Reactive Cyclic Energy (Amplitude)
3979
Apparent or Resultant Cyclic Energy (Amplitude)
11,330
n

FIG. 14.—Stationary vector diagrams of admittance, current, power and cyclic energy in an alternating-current circuit to phase of potential-difference as standard.

and the reactive component $E\,F$ of 750 volts root-mean-square ($E_k = 1061$ volts maximum). The product $I\,E_f$ produces the effective power P_f of eight megawatts amplitude, ($G\,H$ Fig. 12) above and below the average P_m of eight megawatts. The product $I\,E_k$ produces the reactive power P_k of three megawatts amplitude (*H K* Fig. 12). The sum of these two quadrature power components is the total apparent power $I E = P$ of 8.544 megawatts above and below the mean P_m.

The reactive power P_k is associated with a cyclic energy change of $W_k = 0.3979$ myriajoule = 3,979 joules = 405.6 kilogram-meters or 2940 ft-lb. This energy (*M N* Fig. 15) is stored in, or removed from, the magnetic flux of the circuit in one quarter of an energy-cycle, or one eighth of a current-cycle (0.00208 second) over and above a steady stock of energy *o o* (Fig. 13) of equal amount. The total magnetic energy in a current half-cycle is therefore:

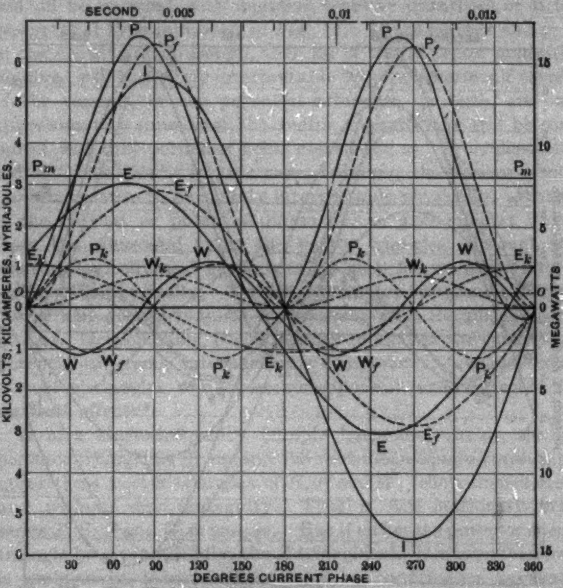

FIG. 13.—Analysis of potential-difference, power and energy to current as standard of phase.

$$2 W_k = I^2 X/\omega \qquad \text{joules per cycle of current} \qquad (18)$$

or 7958 joules (0.7958 myriajoule), at 90 deg. and at 270 deg. of current-phase.

The effective power P_f is associated with a cyclic energy change of $W_f = 1.061$ myriajoule in each cycle (*L M* Fig. 12) above and below the average of eight megajoules per second, or 13.333 myriajoules per current cycle, delivered by the generator outside of the circuit.

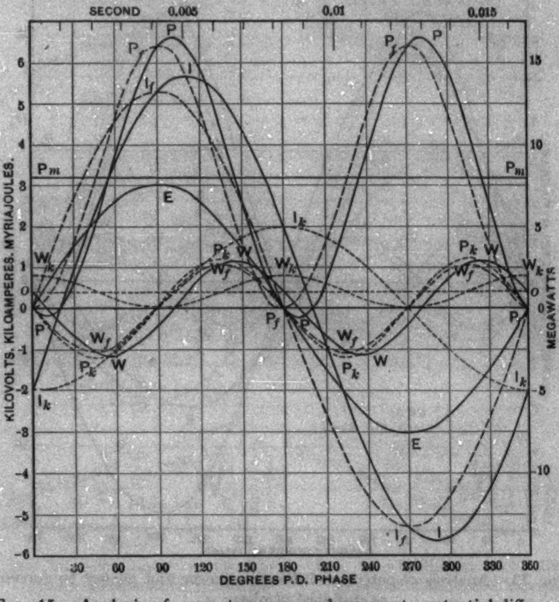

FIG. 15.—Analysis of current, power and energy to potential-difference as standard of phase.

The total cyclic energy change is $W = 1.133$ myriajoule (*L N* Fig. 12) above and below the average of 6.667 myriajoules per energy cycle.

Fig. 12 contains, therefore, a non-rotative impedance triangle *A B C* of ohms, a stationary potential-difference triangle *D E F* of root-mean-square volts, a stationary power triangle *G H K* of maximum cyclic or amplitude watts, and a stationary energy triangle *L M N* of maximum cyclic or amplitude joules. These four non-rotating vector triangles pertain to every alternating-current circuit, considered with reference to the stationary vector current $I\underline{/0}$ root-mean-square amperes. If the circuit contains condensance, instead of inductive reactance, the four triangles will all be inverted, with negative reactive quantities, or of the geometrical type indicated in Fig. 14. If the current and p. d. in the circuit are sinusoidal, then all of the 18 vector quantities involved will be strictly interpretable by simple harmonic theory. If the current, or the potential-difference, or both, are only approximately sinusoidal, the vector triangles may still be computed, and they permit of being considered as " equivalent sinusoidal " triangles.[1] In this case, however, the various vector quantities cease to be strictly interpretable physically. Finally, if the current or potential-difference, or both, depart widely from the sinusoidal type, the vector triangles, although still existing logically and geometrically, may fail completely to be interpreted physically. That is, the vector impedance, voltage, power and energy may be inconsistent with the physical conditions. In such cases, it is necessary to analyze the current and potential-difference into harmonic components, develop a series of vector triangles, one for each component, and aggregate the separate effects.[2]

If in a single-frequency (simple harmonic) circuit, the impedance triangle be given and the root-mean-square current, the other three vector triangles of *E*, *P* and *W*, follow immediately, and without any ambiguity. That is, the stationary-vector series *Z*, *E*, *P* and *W* is unique. But if either the power or energy triangle be given initially, the *Z* triangle which follows therefrom is ambiguous, because there may be condensance associated with the reactance, either in series or parallel, and a doubly infinite system of circuits could therefore be devised that would satisfy the *W*, *P*, and *E* vectors. The only definite conclusion in such a case is that the reactance preponderates over the condensance to the amount indicated by the *X* of the *Z* triangle.

If one or more impressed counter-electromotive forces exists in the circuit, as, for example, that of a synchronous alternating-current motor, the Z diagram that follows from a given P diagram and current I, is logically consistent, and may be practically useful, but is purely fictitious.

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[1] Steinmetz, " The Law of Hysteresis ", TRANSACTIONS A.I.E.E., May, 1894, Vol. 11, pp. 570, 616.

[2] Steinmetz, " Symbolic Representation of General Alternating Waves and of Double-Frequency Vector Products ", TRANSACTIONS A.I.E.E., June, 1899. Vol. 16, pp. 269–304.

If instead of taking the phase of the current as standard, we take the phase of the potential-difference as standard, we exchange $E\underline{/0}$ for $I\underline{/0}$ as the fundamental stationary vector, and we obtain the four stationary vectors Y, I, P, and W of Fig. 14, connected by the relations:

$$I \diagdown\!\alpha = E\underline{/0} \,.\, Y \diagdown\!\alpha \qquad \text{root-mean-square amperes } \underline{/} \qquad (19)$$

$$P \diagdown\!\alpha = E\underline{/0} \,.\, I \diagdown\!\alpha \qquad \text{max. cyclic watts } \underline{/} \qquad (20)$$

$$W \diagdown\!\alpha = (P \diagdown\!\alpha)/(2\,\omega) \qquad \text{max. cyclic joules } \underline{/} \qquad (21)$$

It will be observed that the P and W triangles in Fig. 14 are inverted by comparison with those in Fig. 12, and yet the same single-phase alternator is supposed to be operating on the same circuit in each case. The anomaly is explained by the fact that as shown by Figs. 13 and 15, the resultant power curve P lies intermediate in phase between the current curve I and the potential-difference curve E, so that while the power is leading with respect to the current, it is lagging with respect to the potential-difference. Consequently, the stationary power vector of an alternating-current circuit has, with direct representation, either a negative or a positive angle, according as the phase of one or other of the two quantities E and I is taken as standard, as well as whether the circuit is reactive or condensive.

By comparing Figs. 13 and 15, it will be seen that the curves E, I, P and W, or resultant potential-difference, current, power and energy, all correspond, or may be superposed each on each; but the components E_f, E_k, I_f, I_k, P_f, P_k and W_f, W_k lie on reversed sides of their respective resultants in the two figures, as called for by the two sets of stationary-vector diagrams in Figs. 12 and 14.

It follows therefore that the P and W stationary-vector diagrams exist in two mutually inverted forms for every single-frequency alternating-current circuit; whereas the E, I, Z and Y stationary-vector diagrams are single, their position (erect or inverted), depending upon whether the circuit is inductively or condensively reactant, as well as upon whether direct or inverse representation is employed.

ROTATIVE PROPERTIES OF THE STATIONARY VECTORS $E, I, P,$ AND W

In Fig. 12 the vector $E = I\,Z$ is taken as stationary; but it is of course capable also of being considered as a rotative vector, rotating about the vertex D, with the angular velocity ω. In that case, the three voltages E, E_f and E_k should each be increased in the ratio of $\sqrt{2}$, or should be changed in scale, in order

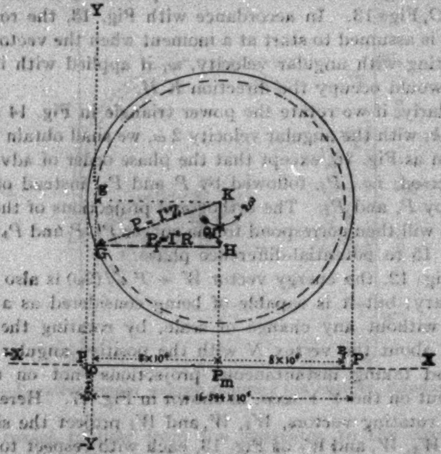

FIG. 16.—Rotative vector power diagram for current standard phase.

that their orthogonal projections on a stationary reference axis, or interceptions on a stationary circle, should correspond to the several instantaneous voltages of impressed potential-difference, effective potential-difference and reactive potential-difference.

In Fig. 12 the power vector $P = I^2 Z$ is also taken as stationary; but it is capable of being considered as a rotative vector without any change of scale, by rotating the triangle $G\,H\,K$, about the vertex K, with the positive angular velocity $2\,\omega$. This is represented in Fig. 16, where K is the center of rotation in the plane $X O Y$ of the paper, $K g = H G$, and the extreme left-hand projection of g is taken at o, as the origin of power coördinates, in the plane $X O Z$ of projection. The projection of K, at P_m, then marks off the steady average power of the system in watts, while the projection points $P P$, marking the limits of the rotating vector $I^2 Z$, indicate the range of cyclic oscillation of the power. Thus, as shown in Fig. 13, the power pulsates between -0.544 and $+16.544$ megawatts once in each power-cycle, or half current-cycle. Similarly, the rotating vector $K H$ projects, with respect to the center P_m, the instantaneous magnitude of the reactive power P_k about the zero line $O O$, Fig. 13. In accordance with Fig. 13, the rotation of Fig. 16 is assumed to start at a moment when the vector current I, rotating with angular velocity, ω, if applied with its center on K, would occupy the direction $K H$.

Similarly, if we rotate the power triangle in Fig. 14 about its vertex k, with the angular velocity $2\,\omega$, we shall obtain the same diagram as Fig. 16, except that the phase order of advance will be reversed; *i.e.*, P_f, followed by P and P_k, instead of P_k followed by P, and P_f. The orthogonal projections of these three vectors will then correspond to the curves P_f, P and P_k as given in Fig. 15 to potential-difference phase.

In Fig. 12, the energy vector $W = I^2 Z/(2\omega)$ is also taken as stationary; but it is capable of being considered as a rotative vector without any change of scale, by rotating the triangle $L M N$ about the vertex N with the positive angular velocity $2\,\omega$, and taking instantaneous projections—not on the $X X$ axis—but on the $Y Y$ axis, as shown in Fig. 17. Here the successive rotating vectors, W_k, W, and W_f project the sinusoidal curves W_k, W, and W_f of Fig. 13, each with respect to its own zero line. At the moment represented in Fig. 17, the current I is supposed to start with angular velocity ω from the position $N M$, with center N, and to project orthogonally on the $X X$ axis.

Similarly, if we rotate the stationary energy triangle $l m n$ of Fig. 14, about the vertex n, with positive angular velocity $2\,\omega$, and project upon the $Y Y$ axis, we shall obtain a diagram like that of Fig. 17, except that the order of vector succession will be reversed, in accordance with the projected curves of Fig. 15.

But the rotating energy vector of Fig. 17 only projects the fluctuation of energy in the circuit. There is, in addition to this fluctuation of energy, a steady stream of energy delivered from the circuit, corresponding to the steady average power

$O\,P_m$ of Figs. 13, 15 and 16. If we represent the steady energy stream by the straight line $O\,P_m$ in Fig. 18, which shows 8 myriajoules in 0.01 second, or at the rate of 8 megajoules per second, then the resultant oscillation of energy, by Figs. 12, 13, 14, 15, and 16, is the sinusoidal curve *W W*, completing two cycles in 1/60th of a second. Superposing the fluctuation on the steady stream, we obtain the broken wavy line *a*, *b*, *c*, *d*, of energy delivered from the generator against time, or current phase, as abscissas. It will be seen that, between 150 and 200 degrees of phase, the energy flow halts, and slightly reverses. At this time, and at corresponding times in successive energy cycles, the energy ceases to flow from the generator to the circuit; but ebbs back from the circuit to the generator.

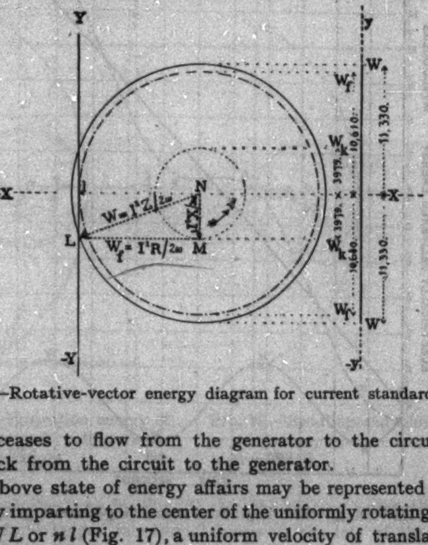

FIG. 17.—Rotative-vector energy diagram for current standard phase.

The above state of energy affairs may be represented projectively by imparting to the center of the uniformly rotating energy vector *N L* or *n l* (Fig. 17), a uniform velocity of translation of P_m joules per second in the direction of the *Y* axis. But this is equivalent to mounting the energy vector on a wheel whose axis is at *N* (Fig. 19), the rotation being on the *X Y* plane. The tread radius of the wheel is made equal to W_f, to joules scale, the flange radius of the wheel is made equal to *W*, to joules scale. A point on the flange is then allowed to project orthogonally on the *Y Y* axis, as the wheel rolls on the *Y Y* rail at the angular velocity 2 ω radians per second. The path of the moving flange point *L*, on the *X Y* plane, will be an oblate trochoid as shown, and the projection of the point, at 24 successive equal time intervals during the motion, is indicated on the line *y y*. It will be seen that the trochoid forms a small recedent loop at the end of its curve, and while the tracing point describes this loop, the energy projection-point undergoes a small recession. If the tracing plane *Y O Z* should move uniformly in the direction *O* −*Z* during the motion, the trace could be made to correspond to the curve *a*, *b*, *c*, *d*, of Fig. 18.

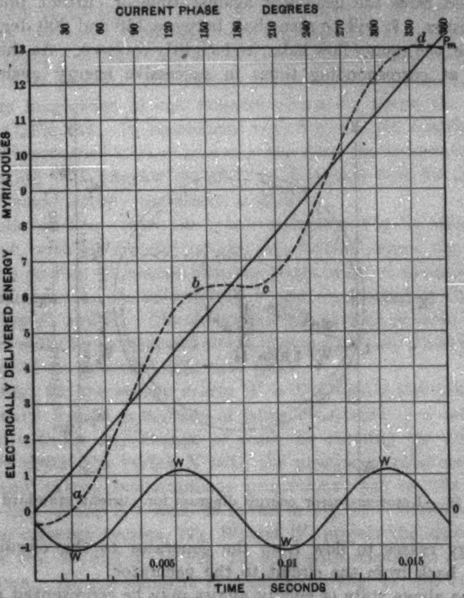

FIG. 18.—Energy-time diagram of alternating-current generator.

If the circuit, instead of being inductively reactive with a power-factor of 0.936, should be non-inductive (with power-factor 1.0), the flange on the rolling wheel disappears. The tracing point then lies on the tread of the wheel. As shown in Fig. 20, the tracing point describes a cycloid in the $X\,O\,Y$ plane, and the recessional loops in the tracing path disappear. The energy delivered by the generator to the circuit then halts at each cycle of energy vector rotation, or turn of the wheel; but it does not reverse.

If, on the contrary, the impedance factor Z/R of the circuit increases, either inductively or condensively, the flange radius bears the same proportion to the tread radius. The oblate trochoid described, as in Fig. 21, by the tracing point on the flange, develops larger recessional loops to the left of the line $Y\,Y$, with more marked reversals of motion and energy in the projected point.

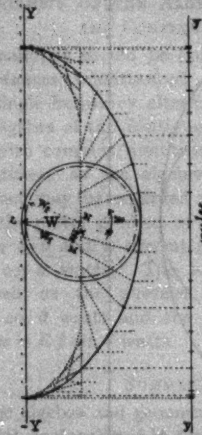

Fig. 19.—Projection energy of rotative- and rolling-vector energy triangle.

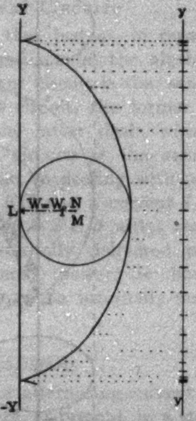

Fig. 20.—Rotating- and rolling-vector energy for non-inductive circuit.

Analytically, if W be the flange radius, and W_f the tread radius of the rolling wheel, the distance of the projected point along $y\,y$ from the initial position at which W lies parallel to the $-X\,X$ axis is:

$$w_t = W_f\, 2\omega t + W \sin 2\omega t \qquad \text{joule-scale cm.} \qquad (22)$$

or substituting for W_f and W their values $P_f/2\omega$ and $P/2\omega$ respectively,

$$w_t = P_f t + \frac{P}{2\,\omega} \sin 2\omega t \qquad \text{joules} \qquad (23)$$

$$\therefore \quad p_t = \frac{d\,w_t}{dt} = P_f + P\cos 2\omega t \qquad \text{watts} \qquad (24)$$

as already deduced from Figs. 13 and 15.

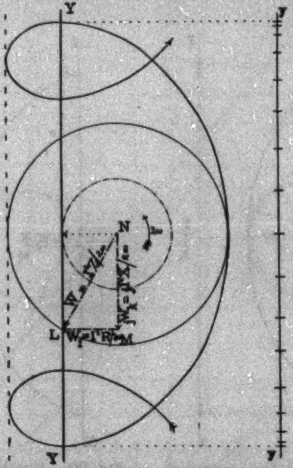

Fig. 21.—Rotative- and rolling-vector energy triangle for circuit of power factor 0.5.

Finally, if the circuit be purely reactive, or resistanceless, the tread radius becomes zero, and the wheel spins without rolling. The path of the tracing point on the flange is then a pure circle. Its projection on the $Y\,Y$ axis is a simple harmonic motion, and on the $Y\,O\,Z$ plane, a pure sinusoid.

Consequently, with suitable convention as to direction and sign of translatory motion, the energy given to an alternating current circuit may be represented by the vertically falling shadow, on the horizontal supporting rail, of a point on the flange of a uniformly rolling wheel. The rate of motion of this shadow will be the power given to the circuit. The average power will be represented by the uniform speed of the axle. The instantaneous power by the instantaneous velocity of the shadow. If a second wheel be geared with the axle so as to rotate in the same direction with half the angular velocity, suitably selected radii on the latter wheel will represent the p. d. and current in the circuit, the instantaneous projections of these radii being measured on a vertical coördinate axis, and not on the horizontal rail.

Conformity of the Algebra of the Alternating-circuit and Continuous-current Circuits

Finally, it should be pointed out that just as, in regard to impedances, admittances, currents, and e.m.fs., the algebra of the single-frequency alternating-current circuit is the same as the algebra of the continuous-current circuit, the former dealing with complex quantities while the latter deals with real quantities;[1] so the algebra of both circuits is the same, or at least may be regarded as the same, in dealing with power. For the power product of an e.m.f. $E\underline{/0}$ and a current $I\underline{/\theta}$, or of an $E\underline{/\theta}$ and a current $I\underline{/0}$, is $E\,I\underline{/\theta} = I\,E\underline{/\theta}$ watts and not $E\,I\cos\theta$ watts. The average externally delivered power, as well as the average instantaneous power, is however $E\,I\cos\theta$ watts and the maximum cyclic internally-reactive power is $E\,I\sin\theta$ watts.

Summary of Conclusions

The algebra and geometry of vector alternating-current technology, as developed in text books, are, at present, in a state of great and unnecessary confusion as to direction of rotation.

The confusion has existed for more than twenty years, and is not confined to any one country or language.

Calling that representation " direct " which denotes a *leading* current as *leading*, in the order of positive rotation, some two thirds of the alternating-current text-books use direct representation, and the remaining one third inverse representation.

The existing dissension relates to conventions and not to facts.

The directions of rotation and representation should be standardized by mutual international agreement.

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[1] This law was first announced by the writer, restricted however to impedances and admittances, in the paper on " Impedance ", Transactions A.I.E.E., April 1893, Vol. 10, pp. 175–232. The law was speedily extended by Dr. C. P. Steinmetz to cover currents and e.m.fs.

The terms "real power" and "wattless power" are inaccurate and misleading.

It is readily possible to compute and discuss the power in an alternating-current circuit as a stationary-vector quantity, without reference to the double frequency of rotative-vector power.

The power developed by any single-frequency alternating e.m.f. E root-mean-square volts on a co-frequent current $I\underline{/\pm\theta}$ root-mean-square amperes, is algebraically $E\,I\underline{/\pm\theta}$ watts. The externally liberated power is $E\,I \cos\theta$ watts, and is usually the principal consideration in power-transmission systems.

In any alternating-current circuit, or portion of the same, there are four non-rotating vectors Z, E, P, W, to standard current phase, and also four Y, I, P, W, to standard potential-difference phase, all connected by ordinary vector arithmetic, and not involving double-frequency products.

The energy in a single-frequency alternating-current circuit follows the projection, upon the rail, of a flange-point on a wheel rolling along the rail with uniform angular velocity. The path of the flange-point is an oblate trochoid for reactive circuits—but is a cycloid for a non-reactive circuit.

The algebra of alternating currents may be regarded as the same as the algebra of continuous currents, for power as well as for other quantities; so that any formula relating to direct-current circuits is also a formula relating to single-frequency alternating-current circuits, when complex numbers are substituted for real numbers.

NOTATION EMPLOYED

$a, b,$ Vector lengths (cm.).

$\alpha, \beta, \theta,$ Vector angles, or phase angles (radians or degrees).

B Susceptance of a circuit, as a whole, or beyond a pair of points in the same (mhos).

c Capacity of a condenser (farads).

$E_0, E\ E_f\ E_k,$ Maximum cyclic, virtual or root-mean-square, effective, and reactive e.m.f. in a circuit, or potential-difference at a pair of points in the same (volts).

e_t Instantaneous voltage or P. D. in a circuit at time t (volts).

$\epsilon = 2.71828 \ldots$ (numeric).

G Conductance of a circuit as a whole, or beyond a pair of points in the same (mhos).

I_0, I, I_f I_k Maximum cyclic, virtual or root-mean-square, effective, and reactive current strength in a circuit (amperes).

i_t Instantaneous current strength in a circuit (amperes).

$j=\sqrt{-1}$ (quadrantal operator).

L Inductance in a circuit (henrys).

l Polar radius-vector of a complex number.

n Frequency of alternation (cycles per second).

ω Angular velocity of a rotating vector, or of an alternating quantity, (radians per second, or degrees per second).

P, P_f, P_k, Resultant, effective, and reactive maximum cyclic power in a circuit (watts).

P_m Average power in a circuit (watts).

p_t Instantaneous power in a circuit at time t (watts).

$\pi=3.14159\ldots$ (numeric).

R, r, Resistance in a circuit, or conductor (ohms).

T, A constant time interval (seconds).

t Elapsed time interval (seconds).

W, W_f, W_k, Resultant, effective and reactive maximum cyclic energy (joules).

w_t Instantaneous energy in a circuit (joules).

X, x, Reactance in a circuit (ohms).

Y, Admittance, or resultant conductance, in a circuit (mhos).

Z, z, Impedance, or resultant resistance in a circuit (ohms).

$X\,X$, $Y\,Y$, $Z\,Z$, Rectangular coördinate axes.

DISCUSSION ON "VECTOR POWER IN ALTERNATING-CURRENT CIRCUITS". JEFFERSON, N. H., JUNE 29, 1910.

C. P. Steinmetz: The standardization of vector notation in alternating current theory is of importance. Considering the difficulty which college students often have to get a conception of one method of vector notation, the existence of two methods, of which the one appears the reverse of the other, evidently is very regrettable. A standardization of vector notation would therefore be very desirable, if feasible. The difficulty is, that we are here in the field of applied mathematics, and in mathematics, the right of priority, and resulting therefrom an international method of notation, is generally recognized. Thus, whatever standard we select, must conform with the existing standards of mathematics, as it obviously would not be reasonable to expect all other sciences to change their notation to conform with our standards; and inversely, no action of ours could exclude from use in electrical investigations, methods which are standard in other sciences.

To explain the situation, we may for a moment discard all the various conventions of vector analysis, which have been proposed in electrical engineering, and go back to the starting point, the conventional methods of elementary mathematics, which the student brings with him when he enters the field of electrical engineering.

In analytic geometry we become familiar with the representation of geometrical figures, curves, etc., by rectangular co-ordinates. Then we learn a second method of representation, by the system of polar co-ordinates, in which the angle represents the independent variable, the radius the dependent variable. We find that the polar co-ordinate system is especially convenient and suitable for periodic functions.

Entering the field of electrical engineering, we meet in the alternating current a function of time, and naturally represent it graphically in rectangular co-ordinates, with the time as abscissae and the current, or voltage etc., as ordinate, by a wave line, the usual sine wave, as shown in Fig. 1, which is familiar to all, even the non technical men; or, if we happen to deal with a current which is not a sine wave, by a wave line of some other shape, for instance like Fig. 2. Such are the records given by the oscillograph.

Now we realize that the alternating current is a *periodic* function of time, and that periodic functions are more conveniently represented by polar co-ordinates. We thus plot the current wave in polar co-ordinates: the angle, ϕ in Fig. 3, is the abscissa of the rectangular co-ordinate representation Figs. 1 and 2, that is, the time t; the radius i is the ordinate, the current, voltage, etc. This gives us as the polar curve, that is, the representation in polar co-ordinates, of the sine wave Fig. 1, the *circle* Fig. 4; the distorted wave of Fig. 2, that is, a wave differing from a sine shape, gives in polar co-ordinates a curve differing from a circle. Fig. 5.

Thus far we have followed the existing international convention of mathematics, and thus far therefore no occasion nor possibility exists for electrical standardization, but we follow the already existing and immovable standards of mathematics.

In many electrical problems, we can replace the distorted wave, Figs. 2 and 5 respectively, by its equivalent sine wave. The polar circle, which represents the equivalent sine wave, is easily derived from the polar curve Fig. 5. It is a circle having the same area as the polar curve of the distorted wave, Fig. 5, and its diameter is the bisector of the area of curve Fig. 5. Thus the representation in polar co-ordinates lends itself very conveniently to the determination of the equivalent sine wave and the effective value of the wave. Irrespective of any further use in vector analysis, the polar co-ordinate system of representation thus is largely employed for deriving the effective value of a distorted wave, and, with the increasing use of the oscillograph will be increasingly used. Thus, in working up oscillograph records, the curve given by the oscillograph (for instance Fig. 2) is replotted in polar co-ordinates (Fig. 5), its area measured by planimeter, and this area, divided by $\frac{\pi}{2}$, is the effective value of the distorted wave, or the value of its equivalent sine wave.

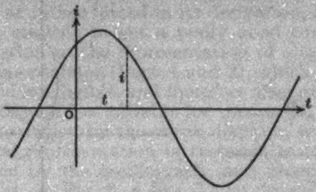

FIG. 1

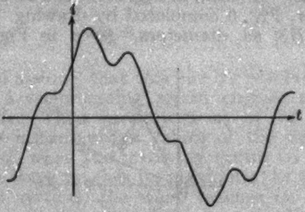

FIG. 2

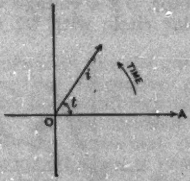

FIG. 3

The circle, Fig. 4, thus is the representation of the sine wave, or of the equivalent sine wave of the distorted wave, in polar co-ordinates.

In those electrical problems, in which we do not have to deal with the instantaneous values, but with the current as a whole, we may omit drawing the circle, but merely give its diameter, $\overline{OI}$ in Fig. 6. Thus, as a natural sequence of the standard methods of analytic geometry, we get in the diameter $\overline{OI}$ of the polar circle the vector representation of the alternating current, voltage, etc. The length $\overline{OI}$ then represents the intensity, its angle $A\,O\,I$ the time, at which the maximum value of the current occurs, that is, its phase. If then, in Fig. 6, $\overline{OI}$ is a current vector, $\overline{OE}$ a voltage vector, Fig. 6 completed by drawing the polar circle with $\overline{OI}$ and $\overline{OE}$ as diameters, gives in Fig. 7 the current wave i, and the voltage wave e in polar co-ordinates.

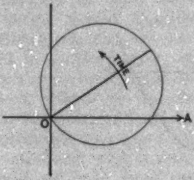

Fig. 4

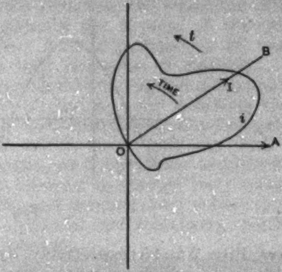

Fig. 5

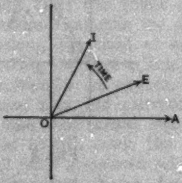

Fig. 6

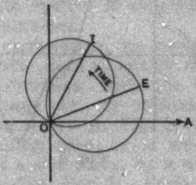

Fig. 7

As shown in Figs. 6 and 7, $\angle A\,O\,I$ is greater than $\angle A\,O\,E$; that is, the current i reaches its maximum, and thereby also any other point of the wave, at a later time, $\angle A\,O\,I$. Then the voltage e reaches its maximum (and thereby also any other corresponding point of the wave) at $\angle A\,O\,E$. That is, current i lags behind voltage e in Figs. 6 and 7.

When, some twenty years ago, I desired to represent alternating waves graphically, I thus used this method as the customary and thereby obvious method of dealing with periodic functions in analytic geometry, rather than attempting to devise a new and different method.

Such a different method has however been devised, in the crank diagram, and is used to a considerable extent. It is the method preferred by a number of engineers, but which always appeared to me as rather forced in its derivation, and thus more difficult for the student to get a really good conception of it, as it has no relation to the representation of alternating waves in rectangular co-ordinates (Figs. 1 and 2), which after all is the most obvious and intelligible, and therefore most generally understood method, though less suitable for theoretical investigation.

In the representation by the crank diagram, we discard altogether the usual representation in rectangular co-ordinates, as for instance given by the oscillograph, and proceed to devise a new method: Let, in Fig. 8, a line $\overline{OI}$ be drawn, which by its length represents the maximum value of a sine wave of current, and assume, that this line $\overline{OI}$ revolves uniformly, like the crank of a reciprocating steam engine, making one revolution per *cycle*. Then the projections of $\overline{OI}$ on the horizontal represent the instantaneous values of the current. At the moment of time, when the revolving vector $\overline{OI}$ passes the horizontal $\overline{OA}$, the wave reaches its maximum; at the moment, when it passes the vertical, the wave reaches its zero value. If, in Fig. 9, $\overline{OI}$ and $\overline{OE}$ represent respectively a current and a voltage in the crank diagram, in the relative position shown in Fig. 9, $\overline{OI}$ lags behind $\overline{OE}$, since during its rotation it passes the horizontal $\overline{OA}$ later, than $\overline{OE}$ passes it. As seen, the crank diagram, Fig. 9, is the reverse, or the image of the polar diagram Fig. 6, and to the casual inspector, familiar with one of the diagrammatic representations, the other diagram thus looks as if it used a rotation in opposite direction, that is, clockwise. This obviously is not the case, but both types of diagrams use counter-clockwise as positive direction.

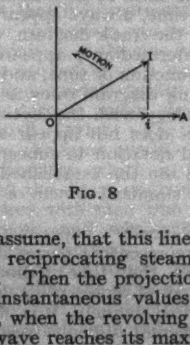

FIG. 8

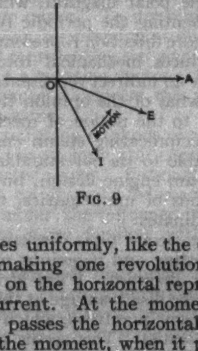

FIG. 9

One of the main objections to the crank diagram is, that it is suitable only for sine waves, and with the increasing importance of wave shape distortion, and the increasing necessity of studying distorted waves, resulting from the rapid extension of the use of the oscillograph, this appeared to me as a very serious objection. To assume, when dealing with distorted waves, that the vector of the crank diagram revolves with a varying speed, or that during its revolution it shrinks and expands in accordance with the deviation of the wave from sine shape, leads to such complication as to be impracticable. This limitation to sine waves appears to me as one of the main reasons, why a standardization of the crank diagram could not fulfil the purpose of securing uniformity of notation, by eliminating the polar diagram, since the latter would still have to be used when dealing with distorted waves, as for instance when working up oscillograph records, etc.

As regards to the terms " direct representation ", and " inverse representation ", used for distinguishing the two methods of representation, these terms obviously are relative only, and either representation would appear as inverse representation to the engineer familiar with the other representation. To me the polar diagram, which uses the time as co-ordinate, in representing the periodic function of time, always appeared as the more direction representation, and the crank diagram, which introduces mechanical rotation as intermediary, appeared as rather an indirect representation of a function of time, and I am somewhat of the opinion that the crank diagram owes its existence to the notion of mechanical analogy with the motion of the reciprocating steam engine, but it does not appear to me desirable to tie our standard electrical notation to conceptions of steam engine design, but rather to use the established conventions of mathematics, that is, the standard system of polar co-ordinates.

The second topic discussed in Dr. Kennelly's paper is a very interesting and ingenious method of representing power in the vector diagram. I am afraid however, that this method has the same disadvantage as the two methods of representing double frequency quantities, which I once devised, namely, it is rather complicated. This seems to be an inherent difficulty resulting from the attempt to represent a double frequency quantity in a single frequency vector diagram.

Gano Dunn: It would be a great advantage if there were uniformity in vector representation, and as we have the International Electrotechnical Commission, a tribunal that has been organized for the very purpose of acting upon questions of this kind, I move that the International Electrotechnical Commission be asked for a ruling upon the standardization of the direction of vector representation.

This will set to work a large body of authorities whose decisions would be respected by technical authors and those finding would contribute toward removing what is now a serious difficulty.

Those of us who have had the advantage of employing engineers brought up at the feet of Dr. Steinmetz know, when those engineers make a certain diagram, what it means, but there are many other engineers educated under other auspices, who mean just the reverse by diagrams that look like Dr. Steinmetz's and the confusion is growing worse every day.

The difficulty cannot be corrected all at once, but it would disappear in time if all future representations should follow as a standard, one or the other of the present forms.

Wm. W. Crawford: As a pupil of Professor Franklin, to whom Dr. Kennelly has given three places in his tabulation of text-books, I do not feel like allowing this opportunity to pass without saying a word in defense of the counter-clockwise rotating vector diagram. In the elementary text-book of trigonometry which I studied, a positive angle is considered as an angle measured from a certain horizontal reference axis to another line which is rotated in a clockwise direction from the reference axis. The sine of the angle is defined as the projection of a unit length of this line on a vertical axis, and the cosine as the projection on the horizontal axis.

When we come to the study of the alternating current, we are taught that it is represented by a sine curve. To my mind no simpler conception can be obtained than by referring at once to the definition of the sine function and representing our sine wave by the projection on a vertical axis of a rotating vector. Since the trigonometric vector rotates counter-clockwise the alternating current vector should do the same.

John B. Taylor: The use of two confusing methods of representing the same conditions in a vector diagram still continues —a condition which is far from satisfactory. Personally, I studied the direct method, but later, on going to Schenectady, I worked with men who had been under the influence of Dr. Steinmetz, and who naturally were more familiar with his "inverse" method.

It seems fair to say that the two methods discourage many from reading the work of others; cause occasional errors in connections and mistaken predictions and conclusions, besides consuming much time and mental effort which have some sort of a monetary equivalent. For these reasons I want to second the motion made by Mr. Dunn that the matter be brought to the attention of the Board of Directors, for whatever additional formality is necessary, to bring the matter to the attention of the International Electrotechnical Commission, with a view to simplifying this double state of affairs.

Dr. Kennelly does not like the term "wattless power". Mr. Thomas is with us to-day, and he made quite extensive use of the term last year—some people thought it was a very good term and some did not like it. Possibly some of the members may have looked over the TRANSACTIONS of the Institution of Electrical Engineers and noted the objections to the term in England. From their published proceedings it appears that objections were raised to the expression " wattless power " in the discussion of a paper, and in defense of the term Dr. Steinmetz was quoted. However, the man who objected to it, said that he did not see that any one other than " a genius unfettered by the ordinary limitations of language " had title to use it.

L. T. Robinson: I also rise in support of the motion. I believe it is the right thing to have this matter referred to some body that will try to decide it in a satisfactory way. Although I have some quite definite views, which are in accordance with Dr. Steinmetz's views in the matter, I think there is no need to put them forth at this time. After hearing the views of two such prominent exponents of the two different ways; at the same time we should have it one way or the other, and have it settled, and I wish to support Mr. Dunn's motion.

C. P. Steinmetz: I also would like to support the motion to refer the matter to the International Commission, because thereby we will have an opportunity to discuss the matter fully. It needs full discussion, before all misconceptions are cleared up. I rotate counter-clockwise, but the quantity which revolves in my diagram is the independent variable, the time, and the vector represents the complete curve of instantaneous values in polar co-ordinates of time. Thus the vector of the time diagram does not represent an instantaneous position, a momentary condition of the periodic wave, but represents the wave as a whole, and the position of the vector is the time of the maximum value of the wave, or of the equivalent sine wave. Thus, on one point we all agree, that counter-clockwise is the positive direction, but the question in dispute is whether in representing alternating waves, we shall consider the alternating wave as represented by the mechanical rotation of a revolving vector, or represented by the stationary vector, of polar co-ordinates of time.

L. T. Robinson: I would suggest that when this matter is submitted to the International Electrotechnical Commission, that Dr. Steinmetz and Dr. Kennelly be asked to submit in behalf of this Institute a brief memorandum covering the facts as they understand them, to aid the Commission in coming to a rapid decision.

Gano Dunn: It was my intention that the question should reach the International Electrotechnical Commission through the American Committee, which would transmit the request of the Convention. Action by the American Committee in bringing the matter to the attention of the Commission would have greater weight if there were the request of this Convention behind it.

It was not intended in referring the question to the Commission that this reference should carry with it any intimation as to which of the two directions of vector representation the American Institute of Electrical Engineers, preferred. My motion was merely to get our difficulty before the Commission for such suggestions or ruling as they might care to make, and I intended that the channel through which it should be presented to the Commission should be the Commission's American Committee. Our Committee might feel unauthorized to present the question unless there was some desire on the part of the Convention, to have it presented.

It appeared at first that a large majority of those present favored direct rotation but this majority might not have been willing to submit the question to the arbitration of the International Electrotechnical Commission, having in mind that submission involved some responsibility for acting according to what the Commission might find.

As a member of the American Committee I wish to place it in the position of feeling authorized to ask for a ruling from the Commission.

The Chairman: You have heard the motion, which is seconded. All in favor signify by saying Aye; contrary, No. (The motion was carried.)

F. Creedy In connection with Dr. Kennelly's very interesting paper on "Vector Power" a short account of a rather different manner of representing it, which occurred to the writer some time ago, may be of some interest. This makes use of the system of point-analysis due to Mobius and Grassmann, which although very well known to mathematicians, has not hitherto received any engineering applications as far as I am aware.

According to this system the power flowing through a given circuit is represented, not by a vector, but by a point, in a manner slightly akin to the Steinmetz "topographic" representation. The rule for the addition of points is, however, entirely different from that in Dr. Steinmetz's system. The point, moreover, in this system is not a mere mark of position but has a number associated with it which is called its "weight." If the "weight" is zero the point is absent. A point may have a negative "weight." This "weight" is used to represent the effective power while the position of the point with respect to the origin represents the reactive power. We establish the following definitions by convention.

Let $S_1 S_2$ be any two points of unit weight and $M_1 M_2$ be the weights which we attribute to them. Then:

Def. 1
$$M_1 S_1 + M_2 S_2 = (M_1 + M_2)\,\overline{S} \tag{1}$$

where $\overline{S}$ is a point having the position of the mass-center of the points S_1 and S_2 when we attribute to them the weights M_1 and M_2. (See Fig. 1). This may be extended to any number of points.

This is the law of point addition. The sum of two points is always in the line joining them and has a weight equal to the sum of their weights.

Def. 2. *The difference of two points of equal weight is the vector joining the points.*

A vector of course has no definite position but may be moved anywhere in the plane.

Def. 3. The effect of adding a vector to a point, say $S+\rho$ is to transport the point from one end of the vector to the other in the direction of the arrowhead on the vector. This follows at once from Def. 2. It is put here merely for convenience. For if

$$S' - S = \rho$$

obviously $$S' = S + \rho$$ See Fig. 2

This may be applied to the representation of alternating current power as follows:

Dr. Kennelly's equation (14) is

$$p_t = P\,\{\cos\theta + \cos(2\,\omega\,t \pm \theta)\} \tag{2}$$

This may be written

$$p_t = P\cos\theta\left\{1 + \frac{\cos(2\,\omega\,t \pm \theta)}{\cos\theta}\right\} \tag{3}$$

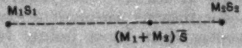

FIG. 1

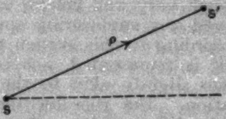

FIG. 2

Case I. All quantities of power which contain no varying component are represented by one point, the origin, associated with a weight corresponding to the amount of power considered.

Case II. Every purely reactive power containing no steady or effective component is represented by a vector exactly as in the ordinary clock-diagram. It shows the position at time *o* of a rotating vector whose projection on an arbitrary axis is $P\cos(2\,\omega\,t \pm \theta)$. The length of a vector representing $\cos(2\,\omega\,t \pm \theta)$ is, of course, unity.

Case III. A quantity of power containing both an effective and a reactive part is represented by adding the vector of case II to the point of case I (the origin). Before we can carry this out properly we must express the power as the product of the effective power, which is the weight of the point, into a unit point. This is done in equation (3) where the expression

$$S = 1 + \frac{\cos(2\omega\,t \pm \theta)}{\cos\theta}$$

represents a unit point at a distance $\frac{1}{\cos\theta}$ from the origin measured along a line making an angle $\pm\theta$ with the axis of reference. See Fig. 3.

Hence we interpret the entire expression (3) as a point at a distance $\frac{1}{\cos\theta}$ from the origin measured in the proper direction, and having a weight $P\cos\theta$. It may be noticed that, as $\cos\theta$ diminishes, the point decreases in weight and at the same time gets further and further from the origin. When $\cos\theta$ vanishes it becomes a point of zero weight at an infinite distance. Now *definition I* gives us the same result when applied to the difference of two points of equal weights, and *definition II* was introduced to remove this ambiguity. *Definition II* enables us to state that:

"A vector is symbolically identical with a point of zero weight at an infinite distance." So that the vanishing of $\cos\theta$ does not introduce any inconsistency but simply reduces case III to case II. In fact, as θ varies the point S moves along the straight line $\overline{S S_0}$ perpendicular to the axis of reference. See Fig. 4.

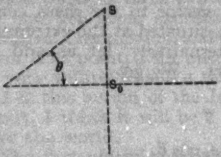

FIG. 3

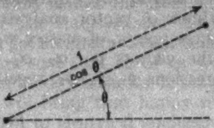

FIG. 4

Suppose we have a number of powers

$$p_1 = \rho_1 \cos\theta_1 \left\{1 + \frac{\cos(2\,\omega\,t+\theta_1)}{\cos\theta_1}\right\}$$

$$p_2 = \rho_2 \cos\theta_2 \left\{1 + \frac{\cos(2\,\omega\,t+\theta_2)}{\cos\theta_2}\right\}$$

$$p_3 = \rho_3 \cos\theta_3 \left\{1 + \frac{\cos 2\,\omega\,t+\theta_3}{\cos\theta_3}\right\}$$

etc.

these may be written, by the principles enunciated above

$$m_1\,(1+\alpha_1),\ m_2\,(1+\alpha_2)\ m_3\,(1+\alpha_3),\ \text{etc.}$$

where $\alpha_1\ \alpha_2\ \alpha_3$ are the vectors representing $\dfrac{\cos\,(2\,\omega\,t+\theta)}{\cos\,\theta}$ etc.

The origin at unit weight, is here typified by the scalar or numeric, 1, and may be called the "scalar point"
Adding these together, we get

$$m_1\,(1+\alpha_1)+m_2\,(1+\alpha_2)+m_3\,(1+\alpha_3)$$

$$=(m_1+m_2+m_3)+m_1\,\alpha_1+m_2\,\alpha_2+m_3\,\alpha_3$$

$$=(m_1+m_2+m_3)\,\left(1+\frac{m_1\,\alpha_1+m_2\,\alpha_2+m_3\,\alpha_3}{m_1+m_2+m_3}\right) \qquad (4)$$

$$=M\,(1+\alpha)$$

The expression

$$\alpha=\frac{m_1\,\alpha_1+m_2\,\alpha_2+m_3\,\alpha_3}{m_1+m_2+m_3}$$

is the well known expression given in the first chapter of every textbook of vector analysis for the vector to the mass center of three points, of masses m_1, m_2, m_3, situated at the extremities of the vectors α_1, α_2, α_3. Or, alternatively, let us add the expressions p_1, p_2, p_3, together direct. We get

$$p_1+p_2+p_3=$$

$$\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3$$

$$+\rho_1\cos\theta_1\,\frac{\cos\,(2\,\omega\,t+\theta_1)}{\cos\,\theta_1}+\rho_2\cos\theta_2\,\frac{\cos\,(2\,\omega\,t+\theta_2)}{\cos\,\theta_2}$$

$$+\rho_3\cos\theta_3\,\frac{\cos 2\,\omega\,t+\theta_3}{\cos\,\theta_3}$$

$$=\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3\left\{1+\frac{\rho_1\cos\theta_1\dfrac{\cos(2\omega t+\theta_1)}{\cos\theta_1}+\rho_2\cos\theta_2\dfrac{\cos 2\omega t+\theta_2}{\cos\theta_2}+\rho_3\cos\theta_3\dfrac{\cos 2\omega t+\theta_3}{\cos\theta_3}}{\rho_1\cos\theta_1+\rho_2\cos\theta_2+\rho_3\cos\theta_3}\right\}$$

which is of exactly the same form as the above expression (4) in vectors so that the appropriateness of the point-analysis is quite clear.

These remarks are already too long, so that I must refrain from giving any applications, of which few have yet been made.

However, for the benefit of anyone who cares to pursue the subject further, I give a few references.

Although the point-analysis is actually due to Möbius and Grassmann, the immediate inspiration of this application, and the notation, is due to Professor C. J. Joly's memoir "The Interpretation of a Quaternion as a Point Symbol" Trans. Royal Irish Academy, Vol. 32, Sec. A, Part 1, further amplified by him in his "Manual of Quaternions" and "Quaternions and Projective Geometry" Phil. Trans. Royal Soc.

The best books on Grassmann's Algebra in the English language are

"The Directional Calculus" E. W. Hyde, (Ginn & Co.), Boston; and "Universal Algebra" A. N. Whitehead, Camb. Univ. Press.

A very rudimentary acquaintance with these subjects is enough to enable one to do much useful work. I do not want to give the impression that the method cannot be used until all these ponderous volumes have been thoroughly mastered.

A. E. Kennelly: I think we all agree, as a result of this very interesting discussion, that vector representation can be arrived at in two ways—by Dr. Steinmetz's method and also by the trigonometrical method, and the fact that we can legitimately divide them in these two ways is what causes the trouble. If we can get some expression from the International Electrotechnical Commission, and if we can get an international decision upon that point, I for one, and I am sure that all of us would be very willing to adopt that one method, whichever it may be, and if this action of the Institute will bring that happy result about, I think it will be a great boon to electrical engineers all over the world.

The first official meeting of the Commission is scheduled for next year in Berlin, but an unofficial meeting is scheduled for this year in Brussels, and if this matter can be brought to the attention of the body at the unofficial meeting this year, it is possible that the work of the body on this subject could be completed in a year's time.

In reference to the able remarks of Dr. Steinmetz, we must all admit that whatever convention is internationally adopted on vector diagram directions, it must not conflict with fundamental mathematics. If it were demonstrable that inverse representation in vector diagrams conformed to the established laws of analytical geometry, whereas direct representation contravened those laws, then it would follow that inverse representation should be followed internationally as a matter of necessity. To my mind, however, no such necessity exists. If we plot a polar-coördinate representation of a voltage and a current, as we have a perfect right to do mathematically, and in the manner described by Dr. Steinmetz, we are not forced to make any vector diagram by drawing diameters to the circles, or equivalent circles, on the curve-sheet. The representation of the vector voltage and current, by straight lines taken on the diameters of their respective circles, seems to be a pure convention, not fundamentally involved in the analytical geometry. This convention of taking the diameters for vectors in a vector diagram, leads indeed to inverse representation, as pointed out in the paper; but another convention might equally well be adopted, which would involve direct representation. For instance, the two polar circles of voltage and current might be brought into line with each other, diametrically, and two separate suitably dephased radii vectors might rotate together, so as to intersect these circles, and represent by their intercepts at any instant, the respective magnitudes of the cyclic quantities. The two radii vectors would then, by convention, represent the voltage and current of the vector diagram, with direct representation. Or convention 4 of the paper might be used, with direct representation, from polar coördinates.

Again, exception may be taken to Dr. Steinmetz's view that the crank diagram " has no relation to the representation of alternating waves in rectangular coördinates ". In a number of text-books, the rectangular-coördinate diagram of a wave is derived from, and made dependent upon, the crank diagram. It seems evident, on deliberation, that a vector diagram is essentially a conventional diagram. That is, it is based upon fundamental mathematics through the medium of some particular convention or conventions. We may safely standardize our conventions without discriminating against the fundamental mathematical operation or laws. Surely it cannot be maintained that because we represent our vectors on paper as having a certain order of angular sequence, that therefore we cannot plot our cyclic magnitudes in any particular coördinate system.

Apart from the preference that springs from mental habits, it is submitted in the paper that either of the conventions here called " direct representation " and " inverse representation " is as good as the other. Each can claim to be descended from pure mathematics, the direct representation from trigonometry, and the inverse from polar coördinates. The only reason claimed in the paper for calling the former *direct* representation, is that when laid off in this manner, the vectors follow in the order of time. The leading vector quantity is ahead of the lagging quantity in the direction of positive rotation.

It is surely of the utmost importance to adopt a standard universal convention of vector sequence and representation. The advantage to each engineer of having one and only one representation in use in alternating-current literature, far outweighs the trouble of having to change one's own familiar method. I would much rather change my own habit in this matter than continue to encounter the perennial medley of different methods of representation in different papers, and I believe that most of our confreres all over the world are of the same opinion.

The important thing is a unanimous agreement. It is of relatively lesser importance which way the decision is taken.

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DETERMINATION OF TRANSFORMER REGULATION UNDER LOAD CONDITIONS AND SOME RESULTING INVESTIGATIONS

BY ADOLPH SHANE

INTRODUCTORY

For some time past the writer has been suspicious of the accuracy of the results obtained in calculating transformer regulation by the now popular method of adding the impedance volts vectorially to the pressure impressed on the load, the data for the impedance triangle being obtained by the common short-circuited secondary method and by the measurement of the resistance of the transformer winding. Indeed, the only check on this method heretofore has been the comparison with the direct method of reading the primary and secondary pressures, reduced to like terms, and ascertaining the difference, or, what amounts to the same thing, reading the secondary pressure under full (current) load and under no load, keeping the primary pressure constant the while. These direct methods are inexact unless great precautions are taken due to the impracticability of reading normal pressures with sufficient degree of accuracy for this purpose.

For example: Suppose the normal e.m.f.s of a transformer can be read to an accuracy of 0.25 per cent and the regulation is actually 2.5 per cent. The value of regulation may be found to be anywhere between 2.25 per cent and 2.75 per cent, causing a possible maximum error of 0.5 per cent in 2.5 or 20 per cent in the value of the regulation.

If some means could be devised whereby the regulation volts might be read off directly by a low-reading voltmeter, results of the same order of accuracy as the reading of normal pressures could be obtained. It is the purpose of this paper to point out such a direct method, as well as an accurate calculated method, to check the results obtained with particular transformers, to point out errors existing in the ordinary calculated method referred to above, and, as far as possible, to give the causes for such errors.

Transformer Regulation

1. *The Direct Method.* If two transformers, *A* and *B* (Fig. 1) exactly alike, be connected to the same source of power their secondaries connected in opposition series, the e.m.f. between the open ends *a b* will be zero until load is applied to one (*A*) of the secondaries, when this e.m.f. is equal to the *true* impedance pressure of the loaded transformer.

If now a third transformer *C* is connected to the line and its secondary connected in series with the other secondaries, but in opposition to *B*, and a galvanometer *G* connected to the free terminals of this secondary series system we have the electrical connections necessary for the proper performance of the test.

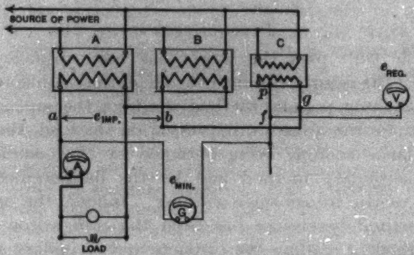

FIG. 1

Normal load is applied to transformer *A*. The secondary winding of *C* is gradually cut out of the circuit, turn by turn, by shifting the contact point *P* along the winding, until the galvanometer *G* reads a minimum. The e.m.f. of the secondary *C* between the points *f*, *g* is the regulation volts required for transformer *A* and may be read off directly by a low-reading voltmeter *V*.

Theory. Fig. 2 represents the common transformer vector diagram using 1 to 1 ratio of transformation for simplicity, with the secondary current I'' lagging θ deg. behind the secondary terminal pressure e''. If to this pressure is added vectorially the secondary resistance and reactance drops ($R'' I''$ and $X'' I''$ respectively, Fig. 2) the secondary induced e.m.f. E'' is the result. This is also the e.m.f. of self-induction of the primary. That part of the impressed e.m.f. which overcomes this latter is designated in the figure by e', equal and opposite in vector position to E''. To this is added vectorially the primary resistance and reactance drops, producing finally the impressed e.m.f., E'.

The foregoing represents the load conditions of transformer *A* in Fig. 1. Transformer *B* being unloaded has a secondary e.m.f. equal and opposite to the primary. Thus in Fig. 2, E' also represents the primary e.m.f. of *B*. Equal and opposite to this is the secondary e.m.f., *E*, which leads the terminal pressure e'' of transformer *A* by a small angle α. The vector difference $c\,a$ of these two e.m.fs. (e'' and *E*), which are respectively the secondary pressures under load and no load, represents the total impedance drop $Z\,i$ or e_{imp} of the transformer (*A*) under load. The vectors $a\,b$ and $b\,c$ are respectively the resistance and reactance drops $R\,I$ and $X\,I$ of the transformer, each being made up as follows:

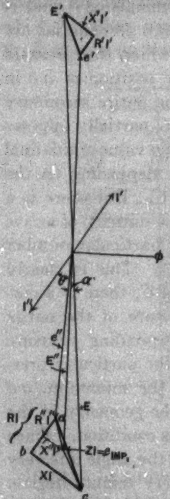

FIG. 2

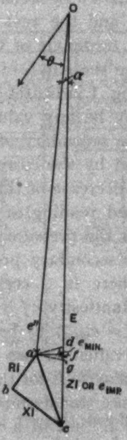

FIG. 3

$$R\,I = R'\,I' + R''\,I''$$

$$X\,I = X'\,I' + X''\,I''$$

The *working* transformer diagram is represented by the two vectors e'' and *E*, capped by the impedance triangle $a\,b\,c$. This is shown separately in Fig. 3 for clearness. The lengths of the vectors e'' and *E* are, however, made longer, without any corresponding increase of the impedance triangle, in order to more nearly represent actual relative conditions.

Consider now the third transformer C. Since it is unloaded and since its secondary is connected in opposing series with B the secondary pressure is exactly 180 deg. opposite to E, the terminal pressure of B, but variable in value, depending on how many secondary turns are in the circuit.

This is shown in Fig. 3, $c\,g$, $c\,f$, or $c\,d$ representing the variable secondary pressure of transformer C, opposing $O\,C$ or E. The only e.m.f. active between the secondary terminals of A and B is the impedance pressure e_{imp}, since these two secondaries are in opposing series. The points $a\,b$ between which this pressure exists is indicated in Fig. 1, and the vector position is $a\,c$ in Fig. 3. The pressure at the terminals of the entire secondary system is $a\,g$, $a\,f$, or $a\,d$, since the e.m.f. of C partially opposes e_{imp}. The instrument G of Fig. 1 indicates the value of this final resultant pressure, which may be any value depending on the number of active turns in the secondary of C. But there is a *definite* minimum value caused by the correct number of active turns in C. Any increase or decrease of this particular number will *always* cause an increased reading of G. This is clearly shown in Fig. 3. With $c\,d$ as the pressure of C, there is a corresponding value $a\,d$ for the secondary pressure of the entire system. Similarly for $c\,g$ there is a corresponding pressure $a\,g$ and for $c\,f$ there is $a\,f$. Manifestly $c\,f$ is the particular pressure of C which causes $a\,f$ $(= e_{min})$ to be the minimum, $a\,d$ and $a\,g$ being each greater in value. From the geometry of the figure e_{min} must be perpendicular to E for this condition. Since in any modern constant pressure transformer the angle a is very small, $O\,f$ differs from $O\,a$ or E'' in but a very minute degree. Hence the difference between E and e'' is very closely $c\,f$. But this difference is the regulation volts sought after. Therefore the regulation volts e_{reg} may be read off directly by a low-reading voltmeter of suitable scale connected to the active secondary terminals of C, after the adjustment for e_{min} has been made.

II. *The Calculated Method.* If the common short-circuited test should give data for the correct impedance triangle, the value of regulation obtained by this means would be above criticism. But such is not the case as will be shown later. The true transformer impedance volts can be found only under actual load conditions. This is e_{imp} referred to above. Hence to find the true impedance triangle the transformer C is dispensed with, the connections of A and B remaining precisely the same. A wattmeter suitable for the full-load current of transformer A and for low voltage, is inserted into the load circuit (W_2 in Fig. 4) the pressure terminals being connected to the free secondary ends $a\,b$, precisely where the low-reading voltmeter V_2 is connected to indicate e_{imp}. The reading of this wattmeter is the true $R\,I^2$ loss of A under load conditions. With the above two readings and the load current the correct impedance triangle may be found. That is, dividing the value of the wattmeter reading by the value of the load current gives the $R\,I$ drop, which together with the impedance drop solves the triangle. From thence on the calculations are as usual in such cases.

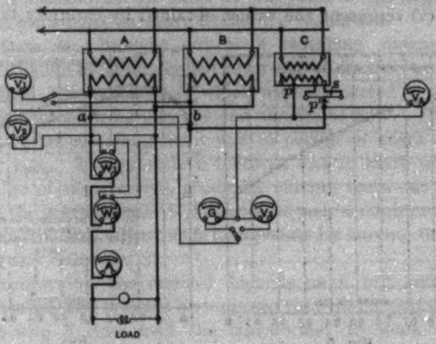

FIG. 4

It may be argued that it might not always prove easy to procure two absolutely identical transformers for the above methods, that the voltage ratios might be just sufficiently different to spoil the test. In answer to this it might be said that the writer had at his disposal three pairs of transformers, each pair of different manufacture, and these checked out very well. The check was made by connecting a delicate alternating current galvanometer to the free ends of the secondaries of each pair connected in opposed series. Scarcely a deflection in any case was observed, though the trifling load of a wattmeter pressure coil connected to the secondaries of one transformer caused sufficient unbalancing to give a decided deflection. This would indicate that absolute voltage equality should be the rule rather than the exception with similar transformers from the same manufacturer. A fairly elaborate test was made to substantiate the above theory, the results of which are incorporated in curves of Figs. 5 and 6. These curves all refer to the regulation volts with respect to power factor, of a particular pair of transformers with noticeably small leakage. Fig. 5 is the curve obtained by the direct method (I) using three transformers. Attention is called to the generous scale of volts in spite of which the observed points appear very consistently on the curve. Curve *A*, Fig. 6, is a duplicate of Fig. 5, without any points being present belonging to this particular curve. The points (.) so near this curve as to seem to form part of it were really obtained by calculation, using method II of this paper. One checks the other. The points (*x*) represent the values obtained by carefully taking the difference between the no-load and load values of e.m.f. $(E - e'')$. Of course the inherent inaccuracy of this method is evident by the staggered position of the points, but they agree closely enough with curve A to confirm the above methods. Curve *B* is the regulation curve obtained by the usual short-circuit test and resistance measurement, and the departure from the three lower sets of results is marked. So decided is the discrepancy that the writer believes, by the use of an ordinary voltmeter, taking full load and no-load readings, the truth is more nearly told. True, the regulation curve is not relatively so consistent and smooth in this latter case, but any point by reasonable care may represent less percentage error than a corresponding point on the calculated curve by the short-circuit test.

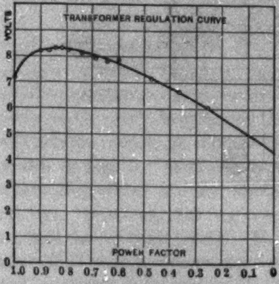

FIG. 5

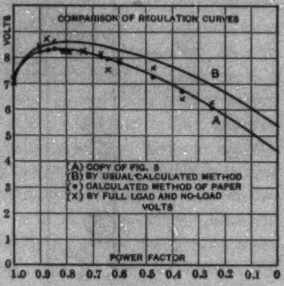

FIG. 6

The Test. More than one set of transformers were tested for regulation, but only a sample of one set of readings are here given. The data for both methods were taken at the same time, the connections for the test being as indicated in Fig. 4. Transformers *A* and *B* were exactly alike, rated at 2 kw. each, with 220 volts secondary. It was found that with 12.5 amperes load (12.56 corrected) no excessive heating ensued, so the current was maintanied at this value. Transformer *C* also happened to be rated at 2 kw. though the value of capacity here is immaterial. The regular secondary winding was not used. Instead, a few turns of wire were wrapped over the fixed windings, care being taken to have a somewhat greater total e.m.f. here than the impedance of transformer *A*, since at one point of the regulation curve, the impedance pressure equals the regulation.

Each turn was brought out to a switching arrangement whereby it could be instantly cut in or out of circuit, excepting the last turn, the terminals of which were connected to a slide-wire resistance allowing perhaps one ampere to flow. The purpose of this latter arrangement was to permit of exact adjustment for e_{min}. The procedure followed was to start with the full number of turns active, gradually cutting them out one by one until the galvanometer *G* indicated as near a minimum value as possible, the final adjustment being made by moving the point *P′* along the slide-wire *S*.

The accuracy of the method depends on *C* not being perceptibly loaded, and it might be supposed that the current through the slide-wire *S* does load the transformer to some extent. That the amount is imperceptible may be shown by a numerical example which closely fits this case. Assuming one volt per turn, 220 volts normal e.m.f., and 10 amperes normal load, we find that this load represents 2200 ampere-turns. The one ampere flowing through the slide-wire connected to the terminals of one turn represents but one ampere-turn. The transformer is thus loaded to less than 0.05 of one per cent, an entirely negligible value.

Voltmeter V_1 was so connected that by means of a switch it could quickly indicate the load and no-load pressures across the terminals of *A* and *B* respectively. V_2 indicated the impedance drop under load conditions, V_3 the minimum volts after adjustment had been made by the use of *G* and V_4 the regulation volts. Actually V_2, V_3, and V_4 were represented by one instrument, a low reading voltmeter, which by suitable switches could be readily thrown to the several points. But one instrument was used to insure correct relative readings for purposes of accurate checks. Wattmeter W_1 was connected to read the load. W_2 having its pressure coil connected to the impedance voltage terminals (*a b* in Fig. 4) indicated the copper $I^2 R$ under load conditions. It had ample current capacity and the pressure coil was adjusted for low voltage. The instrument was found to be accurate for low power-factors. The ammeter *A* indicated the current load which was maintained at 12.56 amperes. The galvanometer *G* was merely a piece of annealed iron suspended in a coil and damped with oil. This proved amply sensitive All the instruments were thoroughly dead beat which vastly facilitated the taking of readings and thus guarded against a change of conditions during the taking of a set of observations.

The load consisted of a lamp bank in parallel with a variable ironless inductance. By this means a power-factor as low as 25 per cent was obtained. Constant temperature conditions were reached before any readings were taken.

TABLE I.

	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*
No.	Amp. load	Watts I^2R	Watts load	Volts load	Volts no load	Volts min.	Volts imp.	Volts reg.	Room temperature C°	Resistance primary by bridge	Resistance secondary by bridge	Power factor $\frac{c}{a \times d}$	Volts reg. $e-d$	Volts reg. calculated	$\sqrt{f^2+h^2}$
1	12.56	89.5	2650	207.7	214.7	4.27	8.29	7.11	24.4	0.252	0.278	1.00	7.0	7.124	8.29
2	"	"	2310	204.0	212.4	0.9	8.24	8.2	24.0			0.901	8.4	8.26	8.25
3	"	"	2240	204.7	213.4	0.8	8.235	8.23		0.252	0.278	0.87	8.7	8.293	8.23
4	"	"	2146	200.0	208.6	0.8	8.30	8.25	24.0			0.855	8.6	8.295	8.29
5	"	"	2095	203.4	211.6	1.02	8.31	8.3				0.82	8.2	8.275	8.36
6	"	"	2023	202.2	210.4	1.34	8.30	8.2		0.251	0.279	0.796	8.2	8.245	8.3
7	"	"	1864	200.8	209.0	1.85	8.33	8.13	25.0			0.738	8.2	8.117	8.33
8	"	"	1728	201.3	209.4	2.45	8.30	7.95				0.684	8.1	7.97	8.32
9	"	"	1618	199.6	207.1	2.8	8.30	7.87	24.0	0.252	0.278	0.645	7.5	7.85	8.35
10	"	"	1497	198.6	206.4	3.21	8.30	7.8				0.60	7.8	7.68	8.45
11	"	"	1168	198.0	205.6	4.232	8.28	7.14	24.0			0.47	7.6	7.14	8.3
12	"	"	925	201.0	207.4	4.97	8.29	6.65				0.366	6.4	6.63	8.3
13	"	"	637	202.0	208.2	5.56	8.26	6.01	24.0	0.252	0.277	0.251	6.2	5.97	8.2

The original data are given in Table I. The sets of readings from 1 to 13 inclusive were taken at nearly normal impressed voltage with power-factors ranging from unity to 25 per cent. This table furnished the data for the curves of Figs. 5 and 6. In Table II the load power-factor was maintained unity, but the e.m.f. was varied from normal to practically zero value. Care was taken to keep the current exactly constant throughout the test.

Inspecting Table I down through the thirteen sets of readings it is seen that with a steady current and voltage about normal (columns *a* and *d*), the copper loss (column *b*), read by W_2 remained constant, though the power factor (column 1) varied from unity to 25 per cent, that is, the real power dropped from 2,650 watts to 637 watts (column *C*). It is also seen that the impedance volts (column *g*) remained sensibly constant during like conditions. The difference between corresponding readings of columns *d* and *e* gives the regulation pressures (column *m*) and as indicated by (*x*) in Fig. 6. Column *h* gives the regulation pressures by the direct method I and columns *a*, *b*, *g* and *l* furnish data for calculating regulation by method II explained above, these calculations being set down in column *n* and plotted as (.) in Fig. 6.

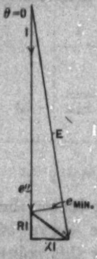

FIG. 7

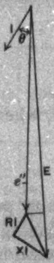

FIG. 8

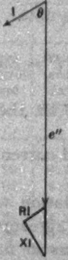

FIG. 9

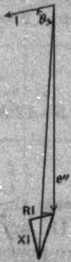

FIG. 10

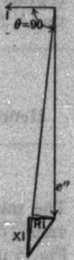

FIG. 11

It might be of some interest to add other checks on the theory of method I. Inspecting Fig. 7, which is the transformer diagram for non-inductive load, it is evident that e_{min} practically equals *X I* in value. Turning to Table I of data, first line column *f*, e_{min} is found to be 4.27 volts. *X I*, when obtained from the correct impedance triangle of method II, was found to be 4.25; a very close agreement. Again, Figs. 7 to 11 are transformer diagrams ranging from unity to zero power-factor. At unity power-factor e'' lags behind E by a small angle α. With diminishing power-factor this angle, Fig. 8, is reduced with a corresponding reduction in the value of e_{min} until some value of power-factor as in Fig. 9 is reached, when both this angle and e_{min} have been reduced to zero and the regulation is represented by the impedance volts. With a further reduction of power-factor, Fig. 10, the angle together with e_{min} again increases with e'' now leading until another maximum displacement is reached at zero power-factor, Fig. 11, when e_{min} is but little different from the $R\,I$ drop. This variation of e_{min} is nicely indicated by the data in column f of Table I. Where its value is about zero the regulation volts should be practically the impedance volts. That such is the case the values of regulation volts of column h testify. Finally at unity power-factor the regulation is practically the $R\,I$ drop, and at zero power-factor it is as closely the $X\,I$ drop. From the data

$$R\,I^2 = 89.5 \text{ watts}$$

Hence $89.5 \div 12.56 = 7.12$, the $R\,I$ drop; where

$$\text{load current} = 12.56$$

The table gives the regulation volts for unity power-factor the value of 7.11, another agreement. Extending the curve of Fig. 5 to zero power factor we find the regulation for this point is about 4.35, which is also but little greater than the $X\,I$ drop.

Check for Accurate Adjustment of e_{min}. The consistency of the curve by method I depends, of course, upon the accurate adjustment of the pointer along the slide-wire S of transformer C. This may be checked directly by repeating an adjustment, as indeed it is desirable to do. A further check may be obtained by the use of the equation

$$e_{imp} = \sqrt{(e_{min})^2 + (e_{reg})^2}$$

That this equation is true may be readily seen by inspection of Fig. 3. If the value of the above radical corresponds closely to the value of the impedance pressure, the adjustment may be said to have been correct. Column o of the Table represents the values of this radical and the corresponding impedance pressures in column g. The agreements here are seen to be rather good, excepting in the tenth line, where the solution of the radical, gives 8.45 while the corresponding impedance pressure is but 8.3. The adjustment here then was hardly exact, with a corresponding inaccuracy in the value of the regulation. Examining the tenth point on the curve of Fig. 5. the inaccuracy is evident. Yet even this error does not amount to much. In other words, an extremely sensitive detector of e_{min} is scarcely necessary. In the test a well damped low-reading alternating-current voltmeter was found to be good enough.

Some Further Investigations

In order to determine the source of the inaccuracy in the usual calculated method for obtaining regulation, the line e.m.f. supplying the transformers under test was gradually reduced all connections remaining precisely as before. The readings taken are given in Table II. It is here seen that the $I^2 R$ (and consequently the $I R$ drop) steadily reduces in value from 89.5 to 86.0 watts. On the contrary the impedance pressure as steadily rises in value from 8.28 to 8.5 volts. That is, as the conditions of the common short-circuit test are approached the copper loss and copper drop become less than under normal conditions of voltage (*i.e.*, normal flux density) while on the other hand the impedance of the transformer is higher in spite of the fact that the $R I$ drop is less. The difference in the two impedance triangles as found by the short-circuit test and the resistance determination, and by method II is clearly seen in

TABLE II

	a	b	c	d	e	f	g	
No.	Amp. load	Watts $R I^2$	Volts load	Volts imp.	Copper drops $b+a$	Reactance drop $\sqrt{d^2-e^2}$	Induced e.m.f.	Remarks
1	12.56	89.5	220	8.28	7.12	4.227	223.4	
2	"	88.5	196	8.3	7.05	4.38	199.4	
3	"	88.0	173.6	8.305	7.01	4.465	177	Load at unity oower-factor
4	"	88.0	147.4	8.32	7.01	4.5	150.8	
5	"	87.5	123.4	8.36	6.96	4.63	126.8	
6	"	86.7	94.2	8.39	6.91	4.75	97.6	
7	"	87.0	71.6	8.44	6.93	4.81	75.0	
8	"	86.7	34.9	8.50	6.91	4.95	69.2	
9	"	86.0	2.0	8.505	6.85	5.05	6.0	

Fig. 12, which applies to transformer *A* of this paper. It is observed that a difference of 20 per cent exists in the value of the reactance drop by the two methods.

The above results are shown in the form of curves in Fig. 13 the abscissas being induced e.m.f.s in all cases. The $R\,I$ and $X\,I$ curves were derived from data forming the $R\,I^2$ and e_{imp} curves. If the slightly parabolic nature of the increase of the copper watts with e.m.f. (*i.e.*, flux density) is due to more than mere chance, this increase may be reasonably supposed to be a true eddy current loss in the copper windings, increasing as the e.m.f. applied to the transformer increases. This additional $R\,I^2$ drop is, no doubt, what is vaguely referred to as "load losses" which disappear as the flux density is reduced to the conditions of the short-circuit test. On the other hand the increase of the $X\,I$ drop with a reduction of the flux density may be due to a somewhat greater permeability of the magnetic circuit. That is, assuming the same leakage magnetomotive forces at low flux densities as at high, the resulting leakage flux will be somewhat greater if the magnetic conductivity is better in one case than another. And at lower flux densities a greater permeability is expected. This, of course, assumes that a part, at least, of the leakage path is through the iron.

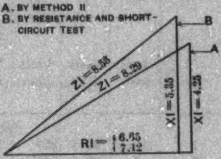

FIG. 12

CONCLUSIONS

It is evident from the foregoing that it is possible to use an accurate direct method for obtaining transformer regulation, the value being read off by a low-reading voltmeter following a simple adjustment. Only commercial instruments and apparatus are needed for the test. It is also evident that accurate data for the calculated method is readily obtainable. Both of these methods are presented with but one object in view, that of commercial utility.

Method I is intended to take the place of the ordinary direct method of reading no-load and full-load pressures. Method II is intended to substitute for the calculated methods now in use. The writer hardly thinks it sufficient to consider the older methods as amply accurate, especially when referring to calculated ones, for though a nice smooth curve may be obtained (because it is a calculated method), the truth is probably more nearly told by the simple expedient of reading no-load and full-load pressures.

Either of the above methods should be available for the average central station and on the test floor of a transformer manufacturing company where like transformers are usually at hand.

APPENDIX

In considering the theory of method II it was assumed that the detail of calculating regulation is generally understood. But to insure this point, a brief outline is here given. Either one of two formulas may be used which lead to like results. These are as follows:

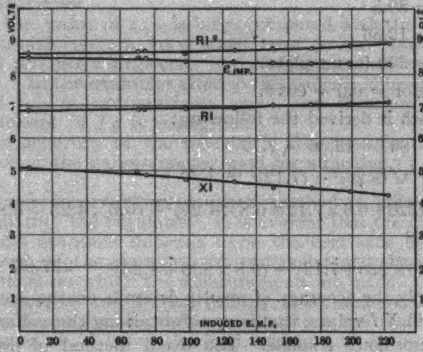

FIG. 13

$$E = \sqrt{(e'' + R\,I \cos\theta + X\,I \sin\theta)^2 + (X\,I \cos\theta - R\,I \sin\theta)^2} \quad (1)$$

$$E = \sqrt{(e'' \cos\theta + R\,I)^2 + (e'' \sin\theta + X\,I)^2} \quad (2)$$

Whereas, in the preceding text,

e'' = the secondary terminal voltage = 100 per cent.

E = the impressed voltage (reduced to terms of secondary) necessary to produce E'' under load.

$R\,I$ = equivalent resistance drop.

$X\,I$ = equivalent reactance drop.

θ = angle corresponding to power factor $\cos\theta$ of circuit.

The difference $E - e''$ is the regulation volts sought. e'' may be assumed to be the voltage stamped on the name plate of the transformer; also θ is assumed. $R\,I$ and $X\,I$ are obtained from the solution of the data entering the impedance triangle.

Each of the above equations is based on correct theory. The first supposes the several e.m.fs. of the transformer to be resolved into components parallel to and perpendicular to e''; the second supposes them to be resolved into components parallel to and perpendicular to the current vector. In either case E is the closing diagonal.

A sample set of calculations will make clear the use of the above equations. Use will be made of the following data which refers to transformer A of this paper:

$e_{imp.} = 8.29$

$R\,I^2 = 89.5$

$I = 12.56$

$e'' = 220$ (name plate)

Power factor $= 0.6 = \cos\theta$.

From which is derived the following:

$R\,I = 89.5 \div 12.56 = 7.12$

$X\,I = \sqrt{(8.29)^2 - (7.12)^2} = 4.25$

$$E = \sqrt{(220 + 0.6\times7.12 + 0.8\times4.25)^2 + (0.6\times4.25 - 0.8\times7.12)^2} = 227.68 \qquad (1)$$

$$E = \sqrt{(0.6\times220 + 7.12)^2 + (0.8\times220 + 4.25)^2} = 227.68 \qquad (2)$$

Manifestly the accuracy of results depends on the accuracy of the $R\,I$ and $X\,I$ values, that is upon obtaining the values for the correct impedance triangle. The usual method of doing this is to short circuit one of the transformer windings (ordinarily the low tension) and impress a sufficient voltage on the other to allow rated full load current to flow. This gives the impedance drop and with a wattmeter inserted also the $R\,I^2$ which divided by the value of the current gives $R\,I$. Or instead of this latter, resistance measurements of both primary and secondary may be made, reduced to like terms, and added. This sum multiplied by the value of the full load current gives the $R\,I$ drop, and

$$X\,I = \sqrt{(\text{Imp. volts})^2 - (\text{R I})^2}$$

It must be remembered that the data by this method is obtained under conditions of low flux density and hence the discrepancy when compared with method II presented in this paper.

DISCUSSION ON "DETERMINATION OF TRANSFORMER REGULATION UNDER LOAD CONDITIONS AND SOME RESULTING INVESTIGATIONS". JEFFERSON, N. H., JUNE 29, 1910.

Charles Fortescue: The method of measuring the regulation of a transformer, given in this paper, appears to the writer to be open to serious objection for the following reasons..

1. Assuming that adjustment for e_{min} has been satisfactorily effected, the reading across $f\,g$ will not be the regulation of the transformer. It is true that in the example cited by the author of the paper the difference between the value read and the true regulation of the transformer, provided all other conditions of the test are satisfactory, would be negligible. But for a transformer having high reactance volts, in comparison with the ohmic drop, this method of measurement would introduce an appreciable error.

2. If the value of e_{min} is large compared with the regulation of the transformer, a very small error in the observation of e_{min} will produce a large error in the adjustment of electromotive force $f\,g$. In the examples cited in this paper it happens that the value of e_{min} is comparatively small, and therefore the error in adjustment of $f\,g$ is negligible.

3. The accuracy of the method is also dependent upon the resistance of the galvanometer used for adjusting $f\,g$ by means of e_{min}.

With reference to the proposed method of obtaining data for calculating the regulation, it is evident that the accuracy of the results obtained depends upon the resistance of the voltmeter used, of the shunt of the wattmeter and the size of the transformers on which the measurements are made. If the two transformers, A and B, are exactly alike, and we denote the true impedance by Z, and assuming that the reading of the voltmeter is V, I being the load current and R the resistance of the voltmeter, we have for the correct value of Z,

$$Z = \frac{V}{I = \frac{2\,V}{R}}$$

all the quantities being combined in their proper phase relations. It is apparent from the above that the value read on the voltmeter is too small for the true impedance volts and the phase difference as obtained by the voltmeter and wattmeter together is too small. If the shunt of the wattmeter has a different resistance from voltmeter, another source of error is added. For small transformers and with the usual commercial low reading voltmeters, the error due to the above conditions may be quite marked.

The curves shown in Figs. 5 and 6 show remarkable agreement between the regulation measured and calculated by the two methods proposed. But it is possible that the errors due to the instruments in both cases are approximately the same.

In Table 2 it is seen that the impedance volts steadily rises in value for a given current as the impressed voltage is reduced. The author argues from these results that the reduction of the flux density may cause increase in the leakage flux due to the higher permeability of the magnetic circuit. In the opinion of the writer, this is very improbable since in the first place the permeability of the iron at the low induction of the short circuit test is in commercial transformers about the same as that at the working induction. In the second place, with primary and secondary windings interlaced, as they are in such transformers, the length of the leakage path in the iron is very small compared with that in the air, and the density of the leakage flux is lower in the iron than in the air, the effect of the reluctance of the iron on the reactance e.m.f. of the transformer is, therefore, inappreciable. It is possible that the difference in impedance with varying induction in the test referred to, may be attributable to a change in the wave form of the primary impressed e.m.f. due to the method of changing its value.

In order to be able to form some estimate of the errors in the method, due to the causes outlined above, it is necessary to have data on the instruments used, and some knowledge of the wave form of the impressed e.m.f. under the various conditions of the test. It would be extremely interesting to obtain a comparison between the short circuit method and that proposed, with all errors in measurements, etc., eliminated.

To conclude, the writer is of the opinion that the results given in this paper are not sufficient as a basis from which to judge the merits of the two methods, of obtaining data for calculating regulation, that is to say, the old method and that proposed by the author. The latter method has had some commercial applications, but for the reasons given in the preceding discussion by the writer has not been widely used.

Results of some tests made on a standard lighting transformer 2200/220 volts 60 cycles

USING METHOD II

Primary volts	Sec. amp.	Volts imp.	Watts
2000	20.2	5.38	76.8
1000	"	5.3	76.8
520	"	5.32	76.8
73	"	5.3	76.8

Corrected average volts impedance = 5.36.
Corrected watts 77.

Using short circuit method

Impedance volts	5.42
Watts	79.70
Amperes	20.2
Corrected watts =	79.4
Volts impedance =	5.42

The difference between the two methods is

Watts	3.2 per cent
Volts	0.8 per cent

This commercially would be considered a good check.

E. A. Wagner: In regard to this paper of Mr. Shane's my views agree with Mr. Fortescue's. I think a small error in measuring the voltage e' by the galvanometer is apt to bring in a large error in the determination of the regulation. The galvanometer undoubtedly will have a certain amount of lag, which will cause an error in the angle, and this error will account for the discrepancy shown on page 1100 in the two impedance triangles. Furthermore, I do not think that the use of three transformers will be a good commercial proposition, as this method of measuring the regulation is intended to be. There is no question but what a simple and accurate means of measuring the regulation directly is very much desired by those having a great deal of transformer work, but I think the method of calculating the regulation through determining the resistance and phase angle of the transformers will give sufficiently accurate measurements and determination of the regulation for commercial purposes.

L. T. Robinson: In reference to Professor Shane's paper it is undoubtedly true that in some transformers at least the regulation may not be accurately found by the usual method of determining the impedance triangle from the volts required to force full load current through one of the windings with the other short circuited.

The required impedance volts may be determined by means of reading the volts and amperes and computing the $I R$ component from the measured resistance of the transformer or the watts can be measured and the energy so read considered to be the $I^2 R$ loss. Sometimes these two methods agree closely and with the measured regulation but sometimes they do not. Also it is necessary to know the regulation and ratio of some transformers especially instrument transformers with very great precision. In fact it may be accepted as a general statement that it is not safe to determine ratio and regulation of transformers by any method of calculation until the method has by accurate measurements been proved correct and reliable for the actual type of transformer to be dealt with.

Although the value of determining the impedance triangle under load conditions, as shown in the paper in Fig. 4, as against determining it by similar means at low density with a short circuited winding seems quite apparent, still the chief reason for believing in it is the excellent agreement between regulation calculated using the values of the impedance triangle determined in this way, and the tested results rather than any theoretical considerations that might be urged in advocating the method used. There are so many secondary actions within transformers that may or may not affect the ratio and regulation that a ready means of determining their effects directly is always of interest and value.

The test that is described is one that requires two or really three transformers. Two of these are exactly alike and the third is a small auxiliary transformer *C*. The voltage of the loaded transformer *A* is connected to one terminal of the small transformer *C* which is connected to have its voltage in the same direction as *A* and opposed to *B*. This small transformer slides, etc., then forms a ready means of getting voltage in phase with *B* varying by small steps.

The point *f* Fig. 3 on *C* corresponding to e_{min} is found and the regulation volts are read from the auxiliary transformer *C*.

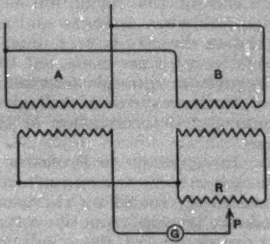

FIG. a

It is not always easy to get two transformers exactly alike. Perhaps some of the most desirable cases where it would be necessary to have an accurate measure of the regulation would be large transformers, where it may be that only one at a time is made. It is, therefore, proper to consider some means whereby the methods of the paper, which are in a sense quite similar, although differently carried out, to methods which have been developed for potential (instrument) transformers may be used to get the same results as those obtained in the paper, without the necessity of employing the two identical transformers.

For the second or unloaded transformer *B* there may be employed any transformer of known characteristics with a resistance across its secondary, and the secondary volts delivered by it changed by a slide resistance *R* Fig. *a*, or the test could be made at low voltage (2200 and under) using resistance on the primary side and omitting the auxiliary transformer altogether, Fig. *b*.

For ratio and regulation testing it is not necessary to have the transformer *B* unloaded (as shown in Fig. 1, Shane) because the phase displacement between primary and secondary current due to carrying moderate load would be small and almost always in a direction to bring the voltage on the secondary of *A* and *B* more nearly in phase so that E_{min} may be read as a smaller value. The regulation will be found from the change in position of the contact ρ between the points where the E_{min} balance for no load and full load on the small transformer *C* is found, the volts per step on *C* being known from a voltmeter in the secondary of *B* or *A*. If the connection of Fig. *a* or *b* is used the absolute ratio also may be read by knowing the resistance *R* and the ratio of transformer *B* accurately. If a standard instrument transformer is used for *B* loading can be so arranged as to get practically zero phase between *A* and *B* at no load on *A*. This is evident from the diagram, Fig. 9, where the impedance volts is in line with the volts e''. The closing voltage *E* will also be along the same line and be in phase with e''. This is the condition where the power factor of the secondary load is the same as that of the impedance triangle of the transformer. Such a condition may be secured in practice by having the load on the transformer *B* reactive or by connecting reactive coils on to load transformer *B* in parallel with its non-inductive load.

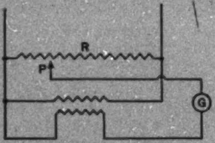

FIG. b.—Arrangement for low voltage, 2,200 and below

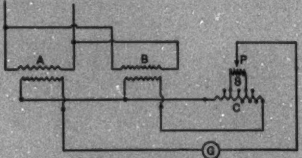

FIG. c.—Arrangement for voltages of 110 to 60,000 or more

For low voltages the resistance *R* may be of any desired amount (about 5 or 10 ohms per volt) and may be used with any suitable detector, (*G*).

For use on 110 to 220- or 550-volt secondaries it would be possible to provide a small auxiliary auto-transformer of known constants with or without the slides, that Professor Shane has shown, refer to Fig. *c*. It would then be easy to get regulation on any transformer of 110, 220 or 550 volts secondary if another transformer to be used as *B* having anywhere near a similar ratio was available without the necessity of getting two transformers alike. For regulation test the constants of transformer *B* need not be accurately known and both ratio and regulation may be obtained if the constants of transformer *B* are known but still *A* and *B* need not be alike. Also with the constants of *B* accurately known proper loading of its secondary can produce zero phase angle. (Zero phase angle is not always present in transformers at no load.) In either case the low reading voltmeter for reading regulation is not required.

If zero phase angle is produced on *B* then the reading of E_{min} where *A* is loaded is also a measure of the phase angle for

$$\text{Sin}\left\{\begin{array}{c}\gamma \text{ in potential transformer}\\ \\ \beta \text{ in current transformer}\end{array}\right\} = \frac{E_{min}}{e''}$$

Quite good accuracy, on account of the very small angle usually found, may be obtained in this way with any suitable means of determining the point *f* and of reading E_{min}. Professor Shane has found that commercial alternating-current voltmeters may be used; also he has employed a special indicator for the purpose. An indicator similar to that described might be used to measure E_{min} as well as to determine the point of, but perhaps some form of dynamometer, separately excited, if need be, and with or without iron might be used, or any thermo galvanometer scheme, or commutator device, in fact any of the special devices referred to at the Convention last year* and this year† in connection with ratio and phase angle testing of instrument transformers.

To me the greatest value of Professor Shane's paper is in showing that the somewhat refined methods by which exact regulation, ratio, etc., may be determined for instrument transformers are useful for, and may be easily applied, to the more general problem of the commercial testing, of lighting and power transformers.

Ralph W. Atkinson: Professor Shane has thrown much light on some complexities of transformer theory. Much of the transformer theory is such that to the ordinary engineer, practical proof is necessary for entire confidence in the results.

It is well known that the effective resistance of a transformer as measured by the wattmeter on short circuit is greater than the effective resistance obtained by measurements with direct current. To determine the correct impedance triangle, the resistance as determined by the wattmeter must be used. Otherwise it is quite possible to make a large error in the determination of the reactance. If there is a difference in the case in point, it would tend to bring the results obtained by ordinary methods nearer to those of Professor Shane. If the results given in Table 2 line 9 be taken as correct for short circuit conditions we may obtain a value of regulation only about $\frac{3}{4}$ as far from curve *A* Fig. 6 as is curve *B*.

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* L. T. Robinson, Electrical Measurements on Circuits Requiring Current and Potential Transformers, A.I.E.E., TRANSACTIONS, 1909.

†Sharp & Crawford, Recent Progress in Alternating-current Measurements A.I.E.E., 1910.

The additional loss as measured by the wattmeter may be of very considerable importance, though generally small in small transformers. It may be calculated by a not very complicated formula while the general explanation of the cause is very simple. The loss may be regarded as due to circulating or eddy currents induced by the field in the coil space due to the load current of the transformer. The field due to the magnetising current is very small and hence causes no loss in the copper. Therefore this copper loss is the same at full voltage as at no voltage. However, Professor Shane's tests show the total copper loss to be greater at the full voltage of the transformer. It would be interesting to know the cause. A possible explanation is the copper loss in the primary due to the exciting current. However the 4 per cent difference in copper loss at full voltage and no voltage can not be accounted for by less than about 4 per cent core loss; moreover this does not account for the reactance on full voltage.

Another point; with transformers connected for a heat run by the ordinary loading-back method, the copper losses are the same as under the short circuit conditions and hence there might be considerable error in the temperature rise obtained on transformers where the "load losses" are large.

It is probable that tests on a transformer having greater proportionate "load losess" would settle definitely their nature. The writer hopes the discussion will bring out the cause of these "load losses"

Adolph Shane: With reference to the errors liable to result in the use of Method I for transformers having large reactance values, as referred to by Mr. Fortescue, I may say that this matter has been given some consideration. The leakage reactance at the worst is always small as compared to the value of normal voltage. Therefore, though I frankly admit that the method is theoretically an approximate one, it affords in nearly every case a truely negligible error. The assumption made is, that the base of a narrow wedge-shaped triangle is equal to the hypotenuse. As long as the angle between these two sides is very small this approximation is legitimate. It would take a leakage reactance of considerable value (third side of triangle) to cause an error of practical importance in the above assumption. By examining the vector diagram of the transformer it will be noticed that this error is a maximum at unity power factor and begins to disappear as the power factor lowers. At one point on the regulation curve the error is theoretically absent, namely when e_{imp} is the value of the regulation. But, excepting near-unity power factor, this error can never be suspected of being important, because the $I\ R$ value is the only other quantity to ever tend to widen out (at very low power factors) the small angle referred to above, and this value is always small as compared to normal voltage.

Therefore, let us consider the worst possible condition, namely at unity power factor, and further let us choose three times the reactance value as observed in the tests. We will consider 12.75 volts as $X I$ instead of 4.25, the other values remaining as before. Under these circumstances the regulation volts is really 7.47. By solving the wedge-shaped triangle e_{reg} is found to be 7.82. The error is thus about 4.7 per cent. This is caused by a phase angle of a little more than 3 degrees between the line and secondary voltages. This displacement is usually considerably less in fairly small capacity transformers.

A word about the galvanometer used in these tests. It was a small piece of iron suspended on a thread. A coil surrounded the iron. Such a detector may be made as sensitive as one pleases and is not intended to indicate quantitative results, but a definite minimum point only. Criticism was made of the lack of sensitive adjustment in the method. Figs. 5 and 6 of the paper seem to show a sufficient degree of accuracy and necessarily assume some precision of adjustment. Indeed, where e_{min} had some value, as at unity power factor, a low reading voltmeter was used at times to secure adjustment more quickly and with good results. Of course, the detector must be well damped. Great accuracy of adjustment is only imperative when e_{min} has some considerable value. Fortunately an alternating current instrument (indicator) is sensitive upon the scale. It is not so sensitive near zero, but neither is extreme accuracy of adjustment necessary when e_{min} is quite small. The accuracy of adjustment may always be checked by the equation $e_{imp} = \sqrt{e_{reg}^2 + e_{min}^2}$. Such checks are often desirable and insure correct results.

The error due to current consumption of instruments is negligible and is of no greater magnitude than might be caused by a voltmeter connection for any test.

As to the use of three transformers in Method I, some may consider such an undesirable complication. If so, I would suggest to them Method II, the calculated method. The work at the desk is the same as in the method now popularly used; only the method of obtaining the data is modified.

As for the present methods of obtaining transformer regulation being sufficiently accurate, it would seem from curves 5 and 6, that the primitive method of reading no-load and full-load voltages, and obtaining the difference may give more accurate results. If we desire the truth, then we should find some scheme for ascertaining the *accurate* value of transformer regulation. Of course, I do not think for a moment that the methods presented here are the only ones feasible for arriving at more accurate results. I merely submitted these two proposed methods for discussion, so as to pave the way toward truth.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., June 29, 1910.

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AMERICAN TELEGRAPH ENGINEERING—NOTES ON HISTORY AND PRACTICE

BY WILLIAM MAVER, JR., AND DONALD MCNICOL

Although there may not be any startling technical announcements to make relative to recent progress in American telegraph engineering practice, yet within the twenty-five years past, in common with the progress in other lines of engineering, substantial developments have been also made in the telegraphic art along numerous lines, such as the standardization of equipment, and the adoption of improved apparatus and methods of operation which have generally resulted in increased efficiency of the plant, greater reliability of operation, a more rapid handling of the traffic, and consequent improvement in the service rendered the public; and which developments have, in fact, been adequate to meet the demands made upon the telegraph.

The time has been deemed opportune to record some of the salient features of present telegraph engineering practice in this country, but first in order more clearly to illustrate the differences between past and modern practice a resumé of the early history of telegraph practice in this country will be essayed in which resumé certain more or less interesting items of information relating to that history perhaps not hitherto published, or in any event not readily available, may be recounted.

The first electric telegraph line in this country was constructed by Morse in 1844 between Washington and Baltimore. The progress of this art into public favor was slow; due mainly to the high rates for service and to more or less imperfect service, the latter due mainly to poorly constructed lines and the former largely to heavy legal expense incurred in the effort to maintain for the Morse interests a monopoly of the telegraphic art. Morse endeavored to obtain a British patent for his electro-magnetic telegraph, but failed on the score of previous publication. Bain of Edinburgh came to the United States in 1848 to obtain a patent covering his chemical telegraph which was refused on the allegation that his device infringed the patents of Morse. Bain's telegraph consisted of a device for perforating long and short holes in a strip of paper, which were used to transmit long and short impulses of current over a wire. At the receiving end he used a sheet or strip of paper saturated with a chemical solution consisting of nitric acid 2 parts, prussiate of potash 20 parts and pure liquid ammonia 2 parts, which solution was decomposed by an electric current from the sending station thereby leaving long and short marks on the receiving paper sheet or strip. Bain pressed his claims in the United States Supreme Court and in the year 1849 a patent was finally allowed. A British patent to Morse would have been of doubtful value at that time, as during the life of the United States patent the Morse telegraph was but sparingly used in Great Britain, various needle and dial telegraph systems having obtained a strong foot-hold in that country.

The maximum speed claimed for the Bain system was about 1000 words per minute, but as a writer of that day remarked:[1] " The process of preparing the message to be transmitted, took quite as long as to transmit it " by the Morse method, and while " Mr. Bain's plan was entirely successful as far as it went it was found that after the quick receipt of a long dispatch, it would take about as long to copy it into manuscript as it would have taken to transmit it in the ordinary manner in the first place." Following the granting of the U. S. patent to Bain, numerous telegraph companies were organized and lines built on which the Bain automatic chemical system was employed, in opposition to the Morse Companies, but in 1850 an injunction was obtained, based on the charge that Bain's apparatus infringed the Morse telegraph patent of 1840. A consolidation of many of the chemical automatic companies with the existing Morse lines soon followed, and subsequently the Morse manual system (in which the Morse stylus recorder, or register was used) went into almost general use.[2] The Morse register was gradually displaced by the reading sounder, but not without opposition on the part of the superintendents of telegraph who were apprehensive, needlessly as experience proved, of the introduction of errors thereby. The first printing telegraph was that due to Royal E. House[3] the use of which was begun in 1847–1848 and continued for many years in this country. This system employed a key-board the depression of a key of which resulted in the printing of a given letter on a strip of paper at the receiving station. The speed of transmission by this system was about 50 words per minute. It was operated on lines 1000 miles in length. The Morse interests endeavored to bring this telegraph printer within the scope of the Morse patents but were overruled by the courts.

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[1] "Electric Telegraph," (1852) Jones, pp. 110-150.

[2] In a personal letter to Mr. Maver dated August 22, 1890, Mr. D. H. Craig who was a prominent figure in the early annals of American telegraphy, writes: " I used Bain's system on lines between New York,

In the early days of the electric telegraph the methods of line construction were naturally crude, but every year saw improvements in the direction of workmanship and materials used. Wooden poles were used from the first in this country, but the forms of insulators and the materials used in their construction were multitudinous, and it was not until much bitter experience was had with various "improvements" in insulators that practice converged on the glass petticoat form now universally employed in overhead electric telegraph work in this country. One of the so-called improvements termed the "brimstone" insulator was especially defective and nearly ruined several of the competing companies that employed it. This insulator consisted of an iron arm which screwed into an augur hole in the pole, the outer end of the arm carried a hollow pendant filled with sulphur into which an iron hook that upheld the line wire was inserted.

Boston and Portland between 1850 and 1853 and was able often in stormy weather to send to the Boston press columns of news when the Morse lines would not telegraph a word. We frequently, however, had trouble with "tailings" when the dots and dashes all ran together and made the record partially or wholly unreliable, so that in a message or series of messages of 500 or 1000 words there would be yards of record that would have to be discarded and the messages repeated. The later use of artificial resistances or magnets largely eliminated this trouble. Bain used on his early lines (for his chemical solution) nitrate of ammonia, 2 pounds to a gallon of water, and muriate of ammonia one pound to a gallon of water, and one-half ounce of yellow prussiate of potassia. This makes a fair solution, but we discarded it, (date not given) and substituted one half ounce red prussiate of ammonia and one pound of muriate of ammonia dissolved in one gallon of pure rain, or distilled water—iron pins were used with this."

[3] Described in "Manual of the Telegraph," Shaffner, p. 391.

The civil war in this country, 1861–1865, again directed the attention of the world to the great utility of the electric telegraph in war and while its use at this time did not perhaps materially aid in the advancement of telegraph engineering it emphasized the value of the Morse telegraph system for this purpose because of its simplicity and reliability in operation.

The source of electromotive force for telegraph purposes in the United States up to the year 1855 was the Grove cell, which was displaced by a modification of the Smee cell known as the Chester battery, and this battery in turn gave way to the Callaud or gravity battery, of which up to the introduction of the dynamo machine in the year 1882, many thousands were in use. In some of the main telegraph offices 5,000 to 15,000 such cells were employed; entire floors of large office buildings being set aside for their occupation.

To meet the increasing demand for additional telegraph facilities in the decade 1870–1880, without resorting to the continual construction of additional line wires, the thoughts of inventors were directed to means for increasing the capacity of existing wires. To this end the chemical automatic telegraph, and the duplex and quadruplex systems of telegraphy were called into service. Thus in 1870 a compound wire of steel core and copper was erected between New York and Washington a distance of 275 miles on which a chemical automatic system due to Mr. George Little was employed. This system was a modification of the Bain chemical telegraph previously mentioned herein. Originally, adequate means were not provided in the Little system for diminishing the "tailings," or prolonged currents, due to the static capacity of the line, at the receiving instrument, in consequence of which the speed of signaling was low. Subsequently Little introduced a plain resistance in shunt around the receiver with beneficial results.

The Varley devices consisting of electro magnets in shunt with the receiver, and of condensers in series with the receiver[4] for the purpose of eliminating the tailings were subsequently employed, (the electro-magnets probably first by H. Grace,) to great advantage in this and certain other later automatic chemical systems in which a single row of holes in the perforated paper (and a uni-directional current) was employed; the condenser as thus employed virtually giving the equivalent of the double current method. Still later the speed of transmission on this New York–Washington line was increased to 900 words per minute by the substitution of an iodine solution and by using a platinum needle in place of a nitric acid solution and iron needle.

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[4] British patent No. 3543, 1862. U. S. Patent 78495, 1868.

An important contribution to the art of chemical automatic telegraphy at this stage was the Edison key-board perforator, which by the depression of a key perforated in a moving paper tape the characters necessary for any given letter. By the Little method of preparing the perforated tape not more than 7 or 8 words per minute was feasible, while with the Edison key-board perforator the tape could be prepared at a maximum rate of 40 words per minute, the average being about 25 words per minute. This key-board perforator while highly ingenious from a mechanical point of view was somewhat cumbersome in operation. The key board was about 18 inches in length, and the keys had a drop of about 2 inches requiring strong pressure to carry them down. As a writer of the period remarked "An hours work on one of these punches is a severe strain on the muscles of a strong man."[5] An important test of this system was made between Washington and New York, January 27, 1874 when the President's message on the Spanish "Protocol" consisting of 11,130 words was transmitted. This matter was prepared for transmission by ten perforators in 45½ minutes. The message was transmitted in 59 minutes. Time from the beginning of perforation until message received at distant end of the wire, 53 minutes. The time consumed in translating the characters by ten operators in New York was about 45 minutes, or roughly it required 72 minutes for the entire operation. Four Morse operators on 4 single wires, it may be remarked, are capable of transmitting a message of this length in 55 minutes. In the practical operation of this system by the Automatic Telegraph Company on its single wire from New York to Washington, D. C., during 1873–1874 business was frequently badly delayed by the breaking of the wire, there being no emergency wire, or alternate route. This fact undoubtedly detrimentally affected the commercial success of this system, a result that must obviously follow in all cases where but one route or only a limited number of wires between the important business centers are available. This automatic system[6] was subsequently employed, more or less in combination with the Morse manual system, on the lines of the Atlantic and Pacific Telegraph Company until the year 1876, when it was gradually displaced by the Morse manual method of transmission.[7]

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[6] (Described in "The Electric Telegraph", Prescott, Vol. 11, p. 727.)

[5] "The Telegrapher," 1875, p. 109.

From about 1880 to 1884 the American Rapid Telegraph Company and its successors the Banker's and Merchants, and United Lines Telegraph Companies, operated a chemical automatic system known as the Foote & Randall system. These companies lines (compound copper coated wires) extended from Boston and New York to Washington, Pittsburgh, Buffalo, Cleveland and intermediate points. In this systemt he double-current method was employed. The prepared paper was perforated in two rows as indicated in Fig. 1.

Dots were represented by one hole on either side of the strip, the dashes by two holes. Consecutive dots, and dashes, were perforated diagonally on alternate sides of the paper strip as shown in the figure. Two metal drums *d*, *d'* connected with the positive and negative poles, respectively, of the battery were placed side by side in such a manner that one drum came under the holes on one side of the paper, the other under the holes on the other side. Transmitting needles or brushes *n*, *n'* connected jointly to the line wire were arranged so that each was in line with one row of holes on the paper. By the arrangement of the holes as shown each consecutive character of a letter, and the first character of a following letter were made by a different polarity to that making the preceding character and consequently all letters containing more than one character were represented by dots and dashes on alternate sides of the received paper strip.

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[7] About the years 1875-77, the widely advertised claims of the Atlantic and Pacific Telegraph Company relative to the advantages of the chemical automatic and Wheatstone automatic telegraph systems controlled by that company were having a depressing effect on the stock of the Western Union Telegraph Company. Presumably to offset this effect President Orton of the last named company contracted with Messrs. Craig, Randall and Foote to pay $500,000 for a chemical automatic telegraph system that would be superior in every respect to that operated by the rival company. Tests were made of the new automatic system and the experts reported that all the technical conditions of the contract were fully met. Upon the sudden death of President Orton shortly thereafter however complications arose, a compromise offer of $250,000 being declined, whereupon the contract was abrogated and the inventors' interests in this system were turned over to the American Rapid Telegraph Company. It may be added on the authority of Mr. C. A. Randall that the inventors finally received about $15,000 as their portion of the amount received for the patents covering the automatic system bearing their name (W. M. Jr.)

At the receiving station needles *n*, *n'* were arranged in series in the line circuit as outlined, and rested on the sensitized receiving paper *p*. As the chemical solution is decomposed only by a current of positive direction, marks were made by the needle *n* with currents from battery *E*, and by needle *n'* with currents due to battery *E'*. In this system advantage was taken of the retardation of current due to the static capacity of the line in forming the dashes; the short perforations, all of uniform length, also limiting the time of contact of battery with the line, and thereby limiting the charge imparted to the line at each contact. The records thus produced were easily read by copyists. This system was capable of transmitting clear, legible characters between New York and Boston at the rate of 1000 words per minute, and 500 words per minute were ordinarily so transmitted. Messages were prepared by operators using the Anderson keyboard by means of which 30 to 50 words per minute could be perforated, the machine operating with the ease of an ordinary typewriter. In June 1883, the American Rapid Company had in operation over 2,400 miles of pole line and 14,000 miles of wire. As already intimated this company began operations with the use of compound wires (6 ohms per mile) consisting of a steel core covered with a copper strip each weighing 200 lb. to the mile. This compound wire proved unsatisfactory, owing it was claimed to imperfections in manufacture which led to breaks or openings in the copper strips admitting moisture and ultimately causing the copper to peel off in long lengths. Subsequently No. 6 iron wire was employed as line wires by this company. The rates charged by this company in 1881 for transmitting messages was $1.00 for 195 words between New York and Boston, but experience showed this rate to be unprofitable and it was increased to 15 cents for 20 words. The Foote and Randall automatic system was set aside in 1884 upon the financial failure of the company.

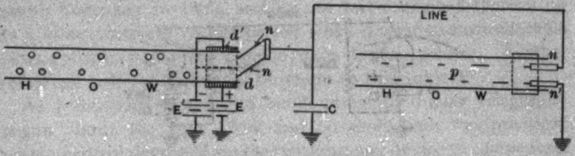

Fig. 1.—Foote and Randall chemical automatic telegraph

In 1881 the "Leggo" chemical automatic system was installed by the Postal Telegraph Company between New York and Chicago (1,000 miles) on its two 1.7-ohm-per-mile wires (compound steel and copper) on which by the Leggo system 1000 words per minute were commonly transmitted. Taylor found by experiments on these wires that up to 400 miles, a speed of 400 words per minute was possible by the old Bain method; that is without compensating for line static,[8] but at a distance of 700 miles the signals arrived in a continuous black line. To remedy this defect Taylor introduced an extra battery *E'*, Fig. 2 at the receiver *R* in opposition to the transmitting battery *E.* The e.m.f. of battery *E'* was one third of that of *E.* *r*, *r'* were adjustable resistances. With this arrangement a speed of 1200 words per minute was possible on this New York-Chicago circuit.

The method of preparing the messages for transmission by the Leggo automatic system consisted in depositing an insulating ink spirally on a revolving metallic cylinder by means of a spout attached to the armature of an electro magnet operated by a relay or Morse key in a main or local circuit. The dots and dashes thus recorded were transmitted from the metallic cylinder at high rates of speed over the line circuit. An advantage claimed for this method of recording signals for re-transmission by Morse telegraphy was that the business originating at branch offices and way offices could be transmitted over through wires automatically without further preparation. The extra battery *E'* was kept constantly to the line during operation and at the instant when the transmitter needle or brush passed onto the insulated ink on the drum this negative polarity cut short the tailings.[9] The Leggo automatic

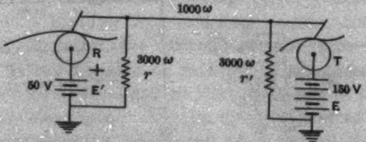

FIG. 2.—Taylor arrangement of Leggo's automatic telegraph

system was abandoned for lack of patronage after a comparatively short period of operation.[10]

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[8] See article of Theodore F. Taylor, *Electrical World*, May 24, 1884.

[9] This arrangement of batteries for this purpose is perhaps suggested in Prescott's "Electric Telegraph," 1866, p. 137.

Since the discontinuance of the American Rapid and the Leggo systems there has been no extensive employment of automatic chemical telegraphs in this country or elsewhere although workers in this field like Anderson and Delany have devised certain features designed to be conducive to greater reliability of operation and speed of translation of the received characters, notably perhaps the Anderson page method of recording the message which enables the attendant to observe the condition of the incoming signals as they arrive, and simplifies the reading of the characters by the copyist[11]. It also lends itself readily to means for drying the paper speedily as received, thus obviating, or minimizing an objection to "wet" strip, namely the tearing of the strip.

The well known Wheatstone system of automatic telegraphy was introduced on certain circuits of the Western Union Telegraph Company in 1883, and its use was continued thereon up to a comparatively recent period when it was[12] to a considerable extent displaced by the Buckingham-Barclay printer. Further reference will subsequently be made to this subject.

As previously stated the employment of duplex telegraphy began about the year 1868, and on short lines was practiced with a certain degree of success without any device to compensate for the static discharge from the main line. Stearns, however, applied the condenser to the artificial line for this purpose in 1872, whereupon the general use of the duplex ensued. Subsequently in 1873–74 the Edison quadruplex was placed in operation on the Western Union Telegraph Company's lines and after numerous modifications of apparatus and circuits finally reached its maximum efficiency about 1884. In the year 1886 there were about two hundred quadruplex sets in operation in the United States, these, it was estimated, providing additional, or "phantom" wire facilities equivalent to 150,000 miles of line wire, the value of which was approximately eleven million dollars.

Much of the success of the quadruplex system between the years 1885–1895 is no doubt properly ascribed to the extensive employment of hard drawn copper wire for telegraph purposes, beginning in 1885. The period indicated was also prior to the advent of high tension power transmission lines in proximity to telegraph circuits, the inductive disturbances from which undoubtedly have had a very detrimental effect upon quadruplex operation, and to which subject also further reference will be made.

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[10] See TRANSACTIONS A. I. E. E., 1897, p. 139.

[11] See "American Telegraphy and Encyclopedia of the Telegraph," Maver, p. 294.

[12] *Ibid*, Chap. XXVII.

As an instance of the extent to which duplex and quadruplex operation has been utilized in this country in proportion to existing wire mileage, it may be noted that in the case of the Baltimore & Ohio Telegraph Company which had a total of 50,978 miles of wire in operation in 1887, (reaching from Portland, Maine to Galveston, Texas, *via* New York, Washington, Chicago, St. Louis, etc.,) 23,482 miles thereof were assigned to the aforesaid duplex and quadruplex service, producing 56,553 miles of phantom circuits. Of the total miles of wire mentioned there were approximately 4,655 miles of No. 12 and 3,605 miles of No. 14 hard drawn copper;[13] 12,726 miles of No. 6 iron, 25,345 miles of No. 8 iron, 3,944 miles of No. 9 iron, and 252 miles of No. 12 iron wire.

In the years 1885–86 the Delany synchronous multiplex system[14] was in experimental operation on a circuit of the Baltimore & Ohio Telegraph Company's lines. On short lines this system gave the equivalent of six transmissions simultaneously, but owing largely to difficulties introduced by the static capacity of the line, its employment on long lines was not available at that time.

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[13] This was doubtless the first extensive employment of hard drawn wire in telegraphy. At this time quite conflicting views were held as to the utility of this metal for overhead telegraph circuits; the advocates of silicon-bronze and phosphor-bronze wire claiming superiority for those materials. The experience of twenty-five years has, however, fully justified the favorable opinions of the pioneer users of hard drawn copper wire regarding its many advantages.

It may be further noted as an interesting item of telegraph history that owing to the expiration in 1880, through inadvertence, of the Canadian patent No. 4608, of April 10, 1875, covering the Edison quadruplex, that system was unprotected by patents in this country after the first mentioned date. A legal contest was, however, waged by the Western Union Company against the Baltimore & Ohio Telegraph Company for infringement of Stern's patent No. 126,847, of 1872, covering the application of the condenser to duplex and quadruplex telegraphy. An injunction *pendente lite* was denied by the courts on the ground that the original Stearns patent had been so broadened by successive re-issues as to raise reasonable doubt as to its validity. The matter was still in litigation when the defendent company was merged with the Western Union Company in October, 1887.

[14] Described in "American Telegraphy," Maver, Chap. XXI.

SOURCES OF ELECTROMOTIVE FORCE IN TELEGRAPHY

As already noted herein gravity batteries as a source of e.m.f. for telegraph service have been almost entirely displaced in this country by machine generators. The type of generators used and the arrangement of equipment vary according to the local requirements.

In some instances the generators are driven by gas or steam power developed on the premises, but as a rule public service mains are utilized to operate the machines, either as motor-generators, or by means of separate electric motors. At points where the only commercial current available is alternating, it is customary to operate from this source an induction motor-driven direct-current generator which in turn furnishes power for the operation of direct-current motor-generators. In numerous cases where driving power to operate the motor generators is derived from public service mains, emergency gas or gasoline engines are installed to insure continuity of service in the event of prolonged interruption of the commercial power circuits. One method of arranging these machines in large terminal offices consists in arranging a certain number of them of equal voltage in series, thereby furnishing a range of e.m.f. from, say 40 to 400 volts, the machines being tapped by the various main line or local wires as required, the local and single wires taking from 40 to 150 volts, respectively, the duplex circuits taking current at 200 volts and the quadruplex circuits at about 350 volts. As currents of both polarities are employed in these systems, two sets or gangs of machines in series, as stated, are employed. Another method of arranging dynamos in terminal offices is to employ from 7 to 14 machines which deliver e.m.f.s ranging from 40 to 400 volts the lower voltage supplying current for the operation of sounder circuits, automatic repeaters, duplex and quadruplex pole changers, transmitters etc. An e.m.f. of 125 volts is used for main line simplex operation, generally way wires having a number of offices on the circuit. Machines supplying respectively 200 volts of positive and negative polarity are allotted to duplex operation, while 385 volt machines of positive and negative polarity, respectively, provide current for quadruplex circuit operation. The general arrangement and appearance of these machines are shown in the accompanying illustration.[15]

Storage batteries also have been utilized quite largely in telegraph service as sources of current for the operation of main line and local circuits. In general these batteries are charged from public service direct-current mains, or by locally operated direct-current motor-generators. The comparatively large loss in transformation of power, from the mains to, and in the storage battery itself, together with the cost of attendance and maintenance of the motor-generators and the battery have acted as a deterrent to its extensive use in telegraph work, notwithstanding certain advantages in the way of constancy and reliability of current that such batteries may possess. The engineering departments of the commercial telegraph companies and of the larger railroad companies have therefore followed closely those developments in the electrical art which aim to procure equally efficient and more economical transformation of electric power for telegraphic purposes, and the claimed advantages of various alternating-current rectifiers—vapor, electro-mechanical, and electrolytic—have been considered and tested. At the present time, for example, quite an extensive application of the electrolytic rectifier is being made by the telegraph companies here, in order to determine what dependance may be placed upon these methods of obtaining practically constant direct-current potentials

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[15] Described in "American Telegraphy," Maver, pp. 47-227.

Fig. 2*a*.—Typical arrangement of motor dynamos in telegraph work

from alternating-current sources. One of these rectifiers (the "Hickley") consists of a solution or electrolyte, say, phosphate of soda, and electrodes of carbon and aluminum, contained in a vessel *V*, Fig. 3, to which are attached radiator loops *R* which permit circulation of the solution (necessary on account of the heat developed in the electrolytic cell) thereby preventing the weakening of any portion of the electrolyte more than another. The direct current supplied by the rectifier is of course, pulsating, but owing to the condenser effect of the cells whereby a portion of the negative current is recovered, currents are derived which are sufficiently steady for average telegraph requirements. With this rectifier 80 volts direct current are procurable from 110 volts alternating current mains. The durability of the solution and electrodes of this rectifier depends largely upon the amount of energy delivered, but if not overworked the rectifier will not require renewal oftener than once each year; assuming daily operation of the device. A suitable transformer *T* is utilized to give either higher or lower voltage than that supplied by the available alternating-current mains, the rectifier being constructed to supply e.m.fs. ranging from 6 to 1000 volts. It may be noted also that some use is being made of small step down transformers of the bell-ringing type for the purpose of obtaining low voltages to operate call circuits, etc., operated in connection with telegraph systems.

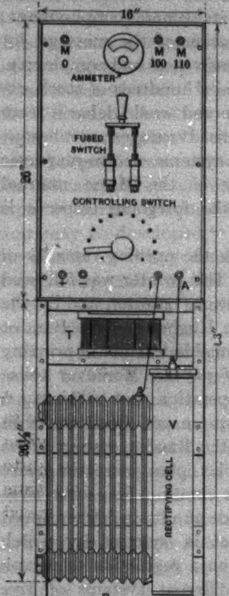

Fig. 3.—The Hickley rectifier

TELEGRAPH PRINTERS

It has long been recognized by certain telegraph authorities, that an ideal system of telegraphy would be a simple and reliable page printer, capable of transmitting and receiving say from 600 to 1000 words per minute on circuits of from 200 to 1000 miles in length. To the inventor of such a system will ensue wealth and fame. It is hardly conceivable, however, that a telegraph printer can be devised that will not possess a number of prominent defects that will act against its general employment; for example, the necessity of preparation of the message for transmission, and its comparative expensiveness and complexity. The first defect would preclude its use on hundreds of stock exchanges and "broker" circuits; the second would debar it from thousands of small way wires. These disadvantages are inherent also in all automatic machine telegraph systems, electro-magnetic or electro-chemical. The superiority of the Morse manual system above all other systems in the foregoing respects is universally admitted.

Reference has already been made in the opening remarks of this paper to the "House" printer. This printer was followed in America by the so-called "Combination" printer, and by the Phelps printer,[16] and in Europe by the Hughes and the Baudot systems, all of which retain the objectionable features of printing the received characters on a strip of paper. Moreover these systems are comparatively slow in operation, not attaining a speed of more than 60 words per minute in one direction, or in each direction if duplexed, although the Baudot system when operated on the synchronous multiplex plan increases quite materially the carrying capacity of a circuit. For some time past in America efforts have been made to obtain higher speed page printing telegraph systems; that is, systems by which the received message will be printed on a regulation telegraph blank ready for delivery. Several different systems of this kind have been recently placed in operation in the United States, namely the Buckingham-Barclay[17] printer on the lines of the Western Union Telegraph Company, the Rowland multiplex printer,[18] experimentally on some of the lines of the Postal Telegraph Cable Company and the Wright printer, to be briefly described presently. The capacity of the Buckingham-Barclay printer is about 100 words per minute in each direction on a circuit 1,000 miles in length with repeaters midway. The capacity of the Rowland printer worked octoplex would be about

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16. See "Electricity and Electric Telegraph," Prescott, Vol. II, p. 652.
17. Described in "American Telegraphy," Maver, Chap. XXVII.
18. Ibid.

280 words per minute on a circuit of moderate length, say 250 miles. The Buckingham-Barclay printer is quite extensively used at present and has been shown to possess marked advantages over its predecessors in printing telegraphy, and as previously noted has supplanted quite largely the Wheatstone automatic system in this country. It is possible, however, that a critical analysis now under way of the respective merits of these systems as regards rapidity, reliability, accuracy, and economy of operation may disclose results somewhat favorable to the Wheatstone system. It is not unlikely that, for the handling of the increased business due to public appreciation of the night "letter-gram" service recently inaugurated by the large telegraph companies in this country, resort may be had to the Wheatstone system or to one or other of the freely available rapid atuomatic telegraph systems mentioned herein, or to others that may be developed.* The merits of the Wheatstone system for service of this general nature has long been recognized in Europe especially in the British Postal Telegraph department where it has attained a speed of from 400 to 600 words per minute on the shorter circuits.

One notable advantage over printing telegraph systems possessed by the Wheatstone or other automatic systems, in which the received messages are translated by a copyist (in common with the Morse manual method, but not by any means to the same degree), is that signals mutilated in transmission that would be beyond recognition in the printed record, may often be deciphered correctly from the tape by an expert operator or copyist. Another important advantage of the Wheatstone system is that its main line apparatus is adaptable either to manual Morse or to high speed transmission by the simple movement of a small switch.

It must be noted, however, that the conditions now surrounding telegraph circuits (referred to elsewhere in this paper), such as high-tension inductive disturbances, and excessive retardation due to the presence of stretches of underground cable, were non-existent when the high speed automatic systems referred to were in practical operation, and these conditions, it may be anticipated, will reduce the speed efficiency in at least direct proportion to the sensitiveness of the respective systems. The night operation of such circuits, would, however, have the advantage of a minimum disturbance from parallel circuits, the exciting cause of which, except the stretches of underground cables, would be less in evidence. Unfortunately this does not apply to static inductive disturbances from adjacent high-potential transmission lines, which are in constant operation.

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*Under this "night letter" service the companies receive not later than midnight fifty word messages (or less) to be transmitted for delivery on the morning of the next ensuing business day at the standard day rate for ten words, one-fifth of the standard day rate for ten words being charged for each additional ten words or less in excess of fifty words in the night message. The companies reserve the option to mail these night telegrams at destination to the addressee. The messages must be written in plain English.

The Wright printer due to Mr. John E. Wright may be operated by ordinary typists unfamiliar with the Morse code, as the transmitter is equipped with a standard typewriter keyboard which may be operated at typewriter speed, and the depression of a key of which selects a combination of positive and negative impulses, which, passing to line select a corresponding letter for printing at the distant receiving typewriter. The electromechanism of the transmitter prints a tell tale duplicate of the outgoing message in page form. The transmitting potential is 385 volts of each polarity. The line instrument is a polar relay of the duplex type that operates locally a magnet which in response to given combinations of incoming currents is designed to control the movements of a type-wheel, capable in operation of selecting and printing a given letter, of revolving around its axis, moving perpendicularly in the line of its axis, and laterally across the message blank at right angles to its axis, all of which movements are reversible. The receiving typewriter prints directly in message form the received telegram, the blanks being fed to the machine by an attendant who watches the copy during the printing to guard against errors. The disposition of the letters of the alphabet the numerals and punctuation marks on the periphery of the type-wheel is such that in practice it is found that regardless of the position of the wheel any letter may be selected and printed with an average of three and one half current impulses from the transmitter. The speed of this printer in operation on lines up to 300 miles in length is about 40 words per minute in each direction.

It may be noted that in America, telegraph operators during recent years have adopted extensively a keyboard, and other semi-automatic devices for the transmission of the Morse alphabet, which devices quite largely increase the rapidity and facility of transmission over the regulation key method. American operators have also very generally adopted the typewriter for transcribing received messages. Primarily these instruments were adopted as labor saving devices, greatly reducing the mental and physical strain on the operator, and making it possible for operators who had "lost their grip" of key or pen, to return to the ranks of first class operators. The public appreciation of the typewritten copy was such also that the telegraph companies encouraged the use of the machine by increasing the compensation of typewriter telegraphers. Further, the use of the typewriter in combination with the marvelous abbreviations employed in the transmission of press matter, by code[19] considerably diminished the demand for rapid automatic or printing telegraphs, at least for that service, by bringing the performance of Morse working well up to what might be expected from printing telegraph systems. The semi-automatic transmitting key termed the Martin mecograph or modifications thereof is used by perhaps four-fifths of the operators of this country. Briefly, it consists of a contact, which when moved to one side manually by the operator makes a dash, and of a vibrating rod or pendulum, that when moved to the other side automatically vibrates (until stopped by the operator) in the act of so doing making any desired number of dots. It is estimated that 60 per cent more movements are required in sending by the ordinary Morse key than by this device, shown in the accompanying illustration, Fig. 3a.

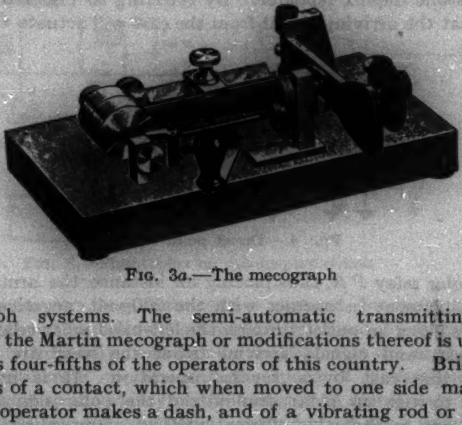

FIG. 3a.—The mecograph

DIRECT POINT REPEATERS

During recent years a demand has grown up for fast duplex telegraph service, in order to provide direct communication between large centres remotely separated. For instance, the vast amount of traffic which arrives at, and which originates at the large eastern cities of this country destined for China, Japan, the Philippines and other Asiatic countries requires that these cities shall have direct communication with the Pacific cable office in San Francisco. Formerly the arrangement of apparatus used in repeating from one multiplex set into another was that whereby the receiving relay controlled the sending transmitter through local connections, but the mechanical inertia of these instruments and the increased number of local contact points through which the operation was controlled did not conduce to high efficiency. The duplex repeater now used on both the Western Union and on the Postal Telegraph lines is known as the "direct point" repeater, and is similar in operation to the Wheatstone duplex repeater. By referring to Fig. 4 it will be seen that the arriving signal from the east will actuate the right hand polar relay $P\,R$, thus placing for instance the armature of that instrument in contact with the 200-volt negative, e.m.f. which is given an outlet through the left hand polar relay to the line west, and signals arriving from the west are relayed to the line east by a reverse operation. It is now customary to wire up polar duplex and the polar side of quadruplex sets so that this efficient method of repeating may be utilized. Inasmuch as the local contact points of the polar relays are in this case employed to deliver line currents, special devices are provided to control local circuits for operating the reading sounders. For instance, in the Western Union type of duplex repeater the polar relays are equipped with double armatures, mechanically jointed together, but separated electrically, one contact controlling the line potentials, and the other the local circuit. The method employed by the Postal Telegraph Company is the well known "leak" arrangement. A single

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[19] See "Phillips Code," W. P. Phillips.

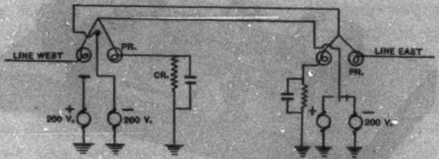

FIG. 4.—Direct point repeater

tap is taken off the armature contact of each polar relay and led to ground through a polar relay and a 20,000-ohm coil. Another method of accomplishing the same result is to substitute a 0.5-m.f. condenser for the 20,000-ohm coil thus obtaining the same response in the polar relay without any loss of current through the leak coil to ground. Indeed when the condenser is used in place of the leak resistance, the polar relay may be done away with, the circuit leading directly from condenser through a sounder and to ground. In this latter case the armature and stop adjustments of the sounder are set so that the signals are all made on the upper stop screw.

The type of duplex telegraphy now universally employed in this country is that in which the well known double-current principle is employed, and by means of the direct repeating relays mentioned, very long distances are spanned, for instance across the continent from New York to San Francisco, by many diverse routes. Ordinarily from four to six repeaters are used in these transcontinental circuits, and the speed of transmission is at least equal to the ability of the operator to manipulate the key. Ordinarily the differentially-wound polarized relay is employed.

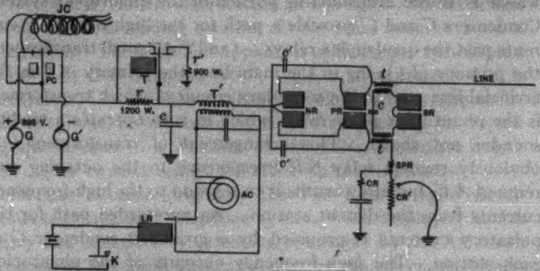

Fig. 5.—Phantoplex on quadruplex circuit

Superimposed Systems. "Phantoplex" and Van Rysselberghe

Since Varley[20] there have been many workers whose aim it has been to increase the capacity of a single wire or a wire already in operation as a duplex or a quadruplex by superimposing thereon one or more pulsatory phantom circuits.

In the accompanying diagram (Fig. 5) is shown an arrangement of a "phantoplex" circuit on a quadruplex circuit that is in actual operation in many places in this country and by means of which a "sextuplex" is obtained.

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[20] Varley's British patent, No. 1044, 1870.

In the figure one station only is shown. *G*, *G'* are the sources of e.m.f., for the quadruplex. *P C* represents the pole changer, *T* the transmitter with its shunt and leak resistances; *N R* indicates the neutral relay, *P R* the polar relay, and *C R*, *C R'* the compensating resistance of the quadruplex system, the local circuits of which are omitted in the drawing for the sake of clearness. As the operation of the quadruplex is generally understood,[21] it will be necessary only to describe the phantoplex portion of the system. *A C* is a high frequency generator, the circuit of which is controlled by a local relay *L R* and a key *K*. In the circuit of *A C* is a transformer *T'* the secondary coil of which is in the transmitting portion of the quadruplex system. Condensers *C* and *C'* provide a path for the high frequency currents past the quadruplex relays. *t* and *t'* are small transformers, the primary of *t* being in the main line, the primary of *t'* in the artificial line; and in the secondary circuit of which transformers is the phantoplex polar relay, which in turn operates a reading sounder not shown. This arrangement of transformers *t*, *t'* obviously renders relay *S R* irresponsive to the outgoing currents of *A C*, but still permits it to respond to the high-frequency currents from the distant station. An unretarded path for the pulsatory currents is provided by a grounded condenser *C* at each station. The high-frequency currents of the phantoplex circuit are of a strength below that necessary to operate the quadruplex relays, but the armature of the phantoplex relay *S R* being properly biased by spring tension responds to the high frequency currents. Incidentally there is shown in this figure at pole changer *P C* a "coil" condenser *J C* known as the "Johnson" coil consisting of three separate coils of German silver wire wound on a wooden bobbin with an air core, the spool being about seven inches long and an inch in diameter. The coils are thoroughly insulated from one another by a double covering of cotton saturated with paraffine. One end of each winding is left open, the other end being connected as shown in the diagram. This device is efficacious in eliminating the sparks at the contact points of the pole changer.

In many cases Morse duplex circuits or portions of them are used simultaneously as telephone circuits, the wires of two such duplex telegraph circuits being employed as one metallic circuit for telephonic purposes. One such arrangement is depicted in Fig. 7. Here *P C*, *P C* may represent the pole changers at a terminal (or a repeating station as shown in Fig. 4) of two duplex circuits, furnished with e.m.f. by generators *G*. The Wheatstone bridge method of rendering the polar relays irresponsive to the home pole changers is used, the arms of the bridge being formed of a double retardation coil *R C* which is found to be an efficient, practical device. In some cases the armatures of the polar relays *P R* are equipped with retractile springs so that the polar duplex apparatus may be availed of for simplex operation when desired, which result is accomplished by disconnecting one contact *b b* of the pole changer from a generator. These relays also have double local contact points on the armature levers *a*, *a′* shown theoretically in the figure, one of which controls the local reading sounder *S*, the other sounder *S′* in a branch office. The telephone apparatus utilizing the two duplex circuits *D C*, *D C* is shown at *T*. *c*, *c*, *c*, *c*, represent 4 m.f. condensers; *i*, *i* are 30-ohm retardation coils. This arrangement of the telephone, in one instance, is used successfully on duplex telegraph circuits to a distance of 360 miles, the entire length of the duplex circuits being 1000 miles without repeaters.

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[21] See "American Telegraphy," Maver, p. 217.

Composite circuits (originally the Van Rysselberghe simultaneous telegraph and telephone system)[22] are employed in this country and Canada very extensively; notably by the American Telephone & Telegraph Company, also by the telegraph departments of several large railway companies. Between New York and Boston alone at least fifty leased telegraph wires are in daily operation on long distance telephone circuits, and this dual use of circuits is being rapidly extended in telegraph practice, all new line construction being designed with this end in view as noted elsewhere herein, the increased earning capacity of the wires thereby gained being the obvious incentive thereto.

INDUCTIVE DISTURBANCES ON TELEGRAPH CIRCUITS

In the pioneer days of telegraphy when routes were being sought for pole lines, the rights-of-way of the existing steam railroads were utilized wherever possible for the obvious reason that, as the proper movement of trains required the constant use of the telegraph, the questions of construction, maintenance, and prompt repairs were thus solved to the best advantage of the railroad and the telegraph companies. The growth of telegraph traffic was however, rapid, and between the larger centres, at least, additional pole lines on highways were soon built to meet the constantly increasing demand for wires. In the course of events also the time arrived when the displacement of the steam locomotive by the trolley car and electric locomotive for train haulage introduced the high-tension transmission circuit, which, being naturally erected along the railroad tracks, at once menaced the value of a railroad right-of-way for telegraph purposes. It developed, also, that long distance transmission lines carrying high-tension alternating currents in numerous instances began to parallel the railroad rights-of-way as generally affording the most direct and favorable routes between cities, thereby adding another disturbing factor to the operation of telegraph lines following the same routes.

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[22] For an account of the first experiments with this system (which has now grown to such large proportions) by Prof. F. Van Rysselberghe in this country (1885-1886), see article in *Electrical World*, October 6, 1888, by William Maver Jr., by whom also it may be of interest to note the first set of Van Rysselberghe's apparatus for simultaneous telegraphy and telephony was by request installed experimentally on a circuit of the American Telegraph and Telephone Company between New York and Philadelphia in the Spring of 1890. (March 1-5.)

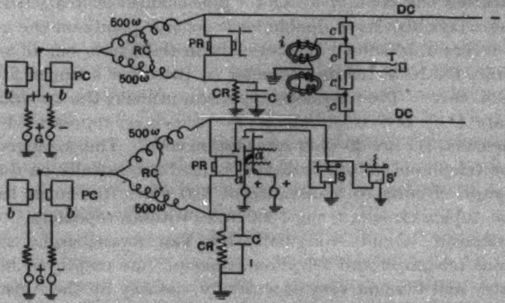

FIG. 6.—Simultaneous (duplex) telegraph and telephone

Apart, however, from the serious inductive disturbances due to the close proximity of such high-tension transmission lines, the subject of inductive disturbances on telegraph lines is not a new one, for mutual inductive disturbances between telegraph circuits were encountered as remotely as 1876 in the dry climate of some of the western states, on lines operated as simplex Morse circuits extending from Omaha, Nebraska to Salt Lake City, Utah.

Upon the introduction of the quadruplex shortly thereafter mutual induction between parallel wires manifested itself as a disturbing element at numerous points, due to the comparatively high e.m.f.s then used on quadruplex circuits, about 300 volts; and as, in the ordinary operation of telegraphy, single wires grounded at each end are employed, the well known method of transposing the wires at intervals to obviate mutual induction effects was not available as a remedy. Fortunately the reduction of efficiency due to this source of inductive disturbance was not very marked, and could, generally speaking, be overcome by an increase of e.m.f. at the terminal stations to 375 or 400 volts.

One of the first methods suggested to eliminate, or ameliorate the disturbances due to mutual induction was devised and tested by Mr. Chas. H. Wilson in 1876, in the western part of this country. The method is indicated in Fig. 7 as applied to single wires*. The object of the arrangement is to set up by means of small transformers *C*, currents in wire *A*, opposite to those induced in wire *A*, by wire *B*, and contrariwise. *R*, *R′* are adjustable resistances, *a*, *a′*, *b*, *b′* are small choke coils. This arrangement was subsequently used on quadruplex lines between Chicago, Buffalo, and Pittsburg, but not very successfully owing to the lag caused by the employment of the transformers *C* in the circuit which augmented the period of reversal to such an extent that the No. 2 side of the quadruplex systems was detrimentally affected thereby.

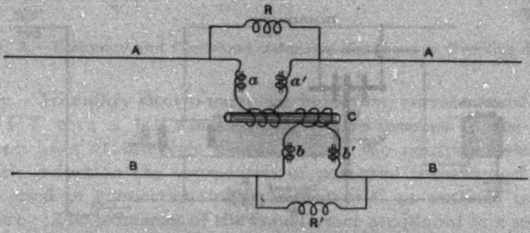

FIG. 7.—Wilson mutual induction neutralizing device

The continual extension of power transmission and other high potential circuits in close proximity to telegraph circuits however created inductive disturbances so inimical to the operation of the telegraph that further means were sought to effect a remedy, short of changing the route of the telegraph pole lines, and a number of corrective devices have been suggested some of which in practice have been fairly successful under certain conditions and in certain localities, but have not always met the requirements elsewhere.

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*See "The Speaking Telephone," Prescott, 1878, p. 362.

One of these means of obviating harmful induction from high tension power circuits on single Morse wires, due to Mr. E. W. Applegate is shown in Fig. 8 in which a resistance *R*, consisting of a carbon stick is connected across the main line contacts of the relay *M L*. By means of this shunt the rapid induced currents from neighboring alternating current circuits are given a path past the relay, and chattering of the armature is further avoided by increasing the tension of the retractile spring *S*. It was found that these devices tended to impede the action of the armature *a*, to overcome which tendency an extra battery *B*, of six cells are added, which by partly magnetizing the relay cores when the armature is on its back stop, effects this result. This device which is termed a " static pick-up " has been successfully used on a number of telegraph circuits where metallic circuits had been resorted to owing to the inductive disturbances from a frequently unbalanced 60,000-volt three phase system that parallels the telegraph circuits for a distance of eleven miles. The employment of this arrangement made it possible to resume single wire operation.

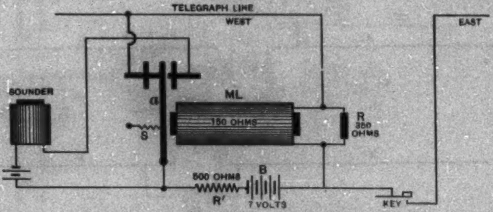

FIG. 8.—Applegate " Static pick up."

Another plan for obviating inductive disturbances on telegraph wires, due to Messrs. Blakeney and Chetwood, is shown diagrammatically in Fig. 9. *A C* is the disturbing line. When key *K* is open the induced currents oscillate harmlessly to earth via *i' c'*, and *n'*, while the regular Morse signals traverse the relay coils *via* the inductive resistance *n*, and non-inductive resistance *n′*, when key *K* is closed.

A brief description will now be given of one of the more recent methods put into practice for the purpose of offsetting inductive disturbances on telegraph circuits due to the close proximity of high tension electric traction circuits resulting from the electrification of the New York, New Haven and Hartford Railway. To nullify electro-magnetic induction, current transformers *C T* with a 1:1 winding, Fig. 10, are inserted in the telegraph lines at intervals of two miles. To neutralize electrostatic induction the secondaries of potential transformers *P T* are used in connection with condensers *C* as outlined in the figure. The primaries of the transformer are placed in a special neutralizing wire or in the disturbing wire itself. By placing a number of secondary coils in multiple, one neutralizing wire may suffice for a number of telegraph wires. As the neutralizing wire is subject to the same inductive effects as the telegraph wires, the currents developed in the former may be arranged to oppose those due to the disturbing wire.[23]

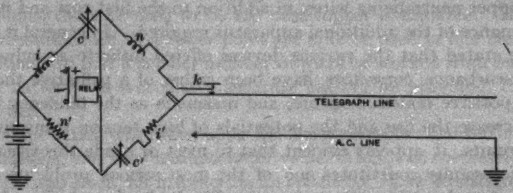

Fig. 9.—Blakeney and Chetwood inductive disturbance diverting device

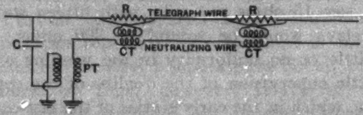

Fig. 10.—Inductive disturbance neutralizing device

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[23] For further details of this general subject see "Telegraph and Telephone Systems as Affected by Alternating Current Lines", J. B. Taylor, Trans. A. I. E. E., Oct. 1909.

It has been found in practice that the neutralizing of inductive effects by the foregoing arrangement is seriously interferred with by escapes from direct current trolley lines which enter and energize the transformers. Variations in load on the alternating current line, phase distortion, etc., also add materially in preventing anything more satisfactory than an amelioration of the harmful inductive effects. Furthermore, in this particular case, the slight improvement noted is obtained at the loss of three copper neutralizing wires, in addition to the first cost and maintenance of the additional apparatus required. In general it may be stated that the various devices offered hitherto as inductive disturbance correctors have been rather of a palliative than of a positive remedial nature, and inasmuch as the tendency is to increase the use and the potentials of high tension transmission circuits, it appears evident that to meet or evade this situation successfully constitutes one of the most serious problems now confronting telegraph engineers. The basis of a solution of the problem may possibly be found in subsequent remarks herein.

MAIN LINE RELAYS

The ohmic resistance of relays used in Morse telegraphy has undergone numerous variations during the past forty years in this country. Relays wound to 1200 and 1500 ohms were not uncommon. At one time the resistance of main line relays was calculated on the assumption that for the best results the total resistance of the relays in a circuit should be equal to the resistance of the line wire.[24] Thus on a circuit 300 miles in length, measuring, say 15 ohms per mile, with fifteen stations on the line, the relays would be wound to 300 ohms. There was, however, little or no uniformity in the winding of the relays and but little supervision of the quality of the copper used in the winding, which in the early sixties of the last century varied in commercial copper from 14 to 85 per cent that of pure copper. Measuring instruments of accuracy were at the time referred to a rarity in this country and no proper methods of ascertaining the condition of the lines as regards electrical resistance and insulation were in vogue. In 1867 the late Mr. C. F. Varley, the well known English electrician, was retained by the Western Union Telegraph Company to visit the United States for the purpose of making a thorough investigation of the electrical conditions of the lines and apparatus of that company.

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[24] "Modern Practice of the Telegraph", Pope, 1869 p. 125.

Following a thorough study of the subject supplemented by hundreds of tests of the lines, insulators, relays, batteries, etc., Mr. Varley presented a voluminous report to Mr. William Orton, President of the Company, December 20, 1867.[25]

The report detailed in extenso, the condition of the equipment as disclosed by the tests, and made numerous recommendations for the improvement of the general service, such as the making of soldered joints, a reduction in the resistance of the relays used, and their re-winding to a uniform resistance of 130 ohms, the wire used to be the best copper obtainable. He also recommended that fewer poles per mile be used in line construction and that a smaller number of wires be worked from one main battery—in fact that a separate battery be provided, for each wire.

Prompt action was taken upon Mr. Varley's report and recommendations, and very marked improvements followed thereafter. Mr. Madison Buell, for instance, in an article on " Low Resistance Relays ",[26] recounts that on the important circuit on which the Atlantic cable traffic between New York and Plaister Cove, N. S., was transmitted the repeaters were found to have relays ranging in resistance from 500 to 1,500 ohms. The relay of the " Milliken " repeater at St. John, N. B., had a resistance of 1,500 ohm. The relays at Boston, Portland, and Bangor had an average resistance of 1,200 ohms. All of these relays were rewound to 80 ohms. Also, many improvements were made in wire jointing, insulation, and leading-in wires at all offices, with the result that whereas on this circuit before these changes were introduced six repeaters were necessary in bad weather and in clear weather three to four repeaters, after the aforesaid improvements were made but two repeaters were required in bad weather, and only one in clear weather to operate the circuit at top speed.

In the course of time, however, relays of 150 ohms were adopted as the standard for simplex Morse circuits. For duplex and quadruplex service the neutral relays were wound to 200 ohms, the polar relays to 400 ohms, (each coil of the differential windings) and for many years these resistances have been the standard. But within the past 8 or 10 years, there has been a still further reduction of the resistance of main line relays (to 37½ ohms) on many of the commercial and railway telegraph way wires with a very pronounced improvement in the operation of the circuits, especially in bad weather. At the present time the tendency of American practice is to the employment of lower e.m.f.s at the terminals of the circuit and to lower resistances in the relays for multiplex working. During the period when No. 9 iron wire was the standard for telegraph purposes, and when the insulation resistance of the lines, was far below present day requirements, a high e.m.f. was necessary in order to maintain proper current values, but by the substitution of low resistance copper conductors in place of iron wire and with improved line construction, the way has been paved for the employment of lower voltages, and relays of much reduced resistance in multiplex operation. Thus some very satisfactory results have been obtained recently in different parts of the country on quadruplex circuits using e.m.fs. as low as 200 volts on well insulated lines of comparatively low resistance (2 ohms per mile) and with polar relays wound to 100 ohms and neutral relays to 50 ohms. The length of the cores of these relays has been somewhat increased. The "potential" resistance of 600 ohms (usually inserted between the current generators and the multiplex apparatus) in these instances has also been reduced to 300 ohms, and the "proportion" resistance and "leak" shunt in the Field key system from 1200 to 600 ohms, and from 900 to 450 ohms, respectively. The objective in these modifications of the prevailing practice is to reduce the mutuul induction between parallel circuits and to render the relays less sensitive to inductive disturbances from any source.

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[25] Report of Cromwell F. Varley, Esq., " On the Condition of the Lines of the Western Union Telegraph Company." Mss. by Mr. J. D. Reid, lithographed. Copies in Wheeler Library, also in Mr. Maver's library and probably in that of the Western Union Telegraph Co.

[26] *Telegraph Age*, Jan. 1, 1903.

SOME TELEGRAPH ENGINEERING DETAILS

It might be supposed that telegraph engineering has to do mainly with purely physical and technical questions, but the close relationship existing between the handling of traffic (telegrams, leased wires, etc.) and the machinery employed in handling it, is such that the telegraph engineer, perforce, finds himself involved in the study of traffic details which he cannot well omit without loss to the economies of operation. This for example obviously requires keeping in the engineer's department an accurate record of existing wire facilities, data as to the daily efficiency of operation of all circuits (especially multiplex and automatic circuits) and information as to their electrical condition, together with carefully prepared tabulated records of details pertaining to methods of traffic movement and the amount of traffic handled on the respective circuits throughout the system, in order at once to enable the engineers to determine whether existing facilities are being utilized to the best advantage, or whether additional facilities, or modifications of the arrangement of present facilities may be deemed advisable. Information of this kind is especially important as a guide in the matter of underground construction and cable work extension. Thorough engineering organization results, amongst other things, in placing the engineer's department in a position to intelligently and promptly decide all strictly engineering and related traffic questions that are continually arising in the operation of a large telegraph system.

The graphic method of mapping circuits indicated in the accompanying diagram Fig. 11 to show at a glance the routes of the various wires, their allotted numbers, how operated, offices entered, material of wire, by whom owned, etc., has been found of great utility wherever used. The scheme which is clearly susceptible of many amplifications was probably first employed in the engineering department of the Baltimore and Ohio Telegraph Company in 1885–88 by one of the present writers and it may be of interest to note that details of the nature indicated relating to over 50,000 miles of actual wire were shown on a map four feet long by 3 feet wide. The accompanying specimens of blank forms for certain reports were also used in the operation of the same company, the information derived therefrom enabling the engineer's department to maintain an intelligent supervision of the circuits that resulted in a clearly perceptible enhanced earning capacity in the case of numerous circuits. Somewhat contrary to

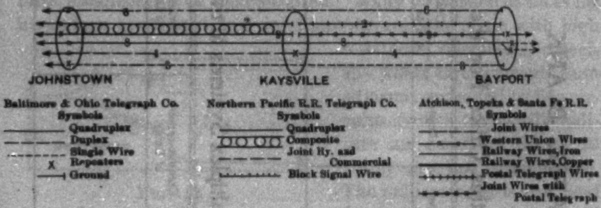
JOHNSTOWN
KAYSVILLE
BAYPORT
Baltimore & Ohio Telegraph Co. Symbols
Quadruplex
Duplex
Single Wire
X Repeaters
Ground
Northern Pacific R.R. Telegraph Co. Symbols
Quadruplex
Composite
Joint Ry. and Commercial
Block Signal Wire
Atchison, Topeka & Santa Fe R.R. Symbols
Joint Wires
Western Union Wires
Railway Wires, Iron
Railway Wires, Copper
Postal Telegraph Wires
Joint Wires with Postal Telegraph

Fig. 11.—Graphic method of mapping telegraph circuits

TRAFFIC BLANK

To ______________________ Supt. CLEVELAND, O., FEBRUARY 15, 1886

Statement of Messages Handled in this Office For the Week Ending ____________

No. of Circuit	From	To	Single	Duplex	Quadraplex		Dates. Messages Sent and Received.						
					A Side	B Side	1	2	3	4	5	6	7

To ______________________ Supt. INDIANAPOLIS, IND., FEBRUARY 13, 1886

Report of the Working of the Single and Multiplex Systems in this Office, Week Ending Sat., Feb. 20

Date	Name of Circuit	How Assigned	Commencement of Delay	Termination of Delay	Nature of Delay

expectations these reports were prepared by chief operators or clerks at no additional expense. As will be readily understood the knowledge that the operation of all circuits was under constant impartial supervision was not overlooked by those directly in charge of the operation of the circuits.

A comprehension of the condition of the insulation resistance and conductivity of every circuit, open or in cables is manifestly of great importance to the engineering department and reports of the tests of conductors for these properties are promptly forwarded to the engineer's department periodically.

The Telephone in Electrical Testing

In America the tangent galvanometer has long since been set aside and simpler and quicker methods of circuit testing and fault localizing have been adopted. Many tests, such as those for insulation resistance and conductivity are now made with high resistance voltmeters, especially where earth currents from adjacent grounded trolley circuits (which frequently indicate an e.m.f. of 15 to 20 volts) are not troublesome. The milliammeter is also used for making insulation resistance measurements not exceeding one megohm and for other electrical tests. The telephone receiver is used as an indicator in many tests. This instrument in connection with an "exploring" coil is largely utilized for localizing faults in aerial cables and in underground cables, especially where the latter are laid in conduits. In making these tests a high frequency current is established in the defective conductor and the exploring coil, a semi-circular coil of fine wire in circuit with the telephone, is moved from point to point along the cable sheath, the indications in the telephone increasing or diminishing as the defect is reached. The telephone receiver as a testing device is particularly advantageous for practical purposes as it places in the hands of the electrical worker or "trouble hunter", an instrument at once portable, and easily understood, and one that is not readily deranged by rough handling. Where a head-band is used to support the receiver the hands of the workman are free.

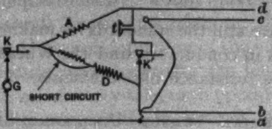

Fig. 12

For quickly determining by means of the telephone as an indicator the distance of a break in a cable conductor when the insulation is normal, one method is as follows: Select three conductors similar electrically to the open conductor *b* and adjacent to each other, *a*, being next to *b*; *c*, being next to *d* and connect as shown in Fig. 12. *G*, is a source of alternating current. For cables approximating 1000 feet in length the generator should give from 40 to 130 volts. The resistance of arm *A* may require to be 100, or 1,000 ohms. To make this test the four wires should be opened at the distant end. Keys *K*, *K′* are then closed and the resistance of arm *D* or rheostat is varied until minimum sound is heard in the telephone receiver, when:

$$\frac{L\,R}{R'} = F$$

where L is the length of the cable in feet, R, the resistance of arm A, R' the resistance of rheostat D, and F is distance to break in feet.

The Varley and Murray tests are still the standards for making accurate measurements for faults in conductors, and the Wheatstone bridge method for accurate resistance measurements.

POLE LINE CONSTRUCTION—AERIAL VERSUS UNDERGROUND CONDUCTORS—NOTES ON DUPLEX AND QUADRUPLEX OPERATION

Owing to the confusion and general disarrangement of business that usually follows the prostration of the telegraph wires by severe sleet or wind storms in this and other countries, every notable occasion of this kind has been followed by insistent demands on the part of the interested business communities that measures be taken to prevent a recurrence of these disarrangments. So much has this been the case that in Great Britain, at least, where such storms are quite frequent, and where owing to the geographical shape of the country the loss of telegraphic communication due to the effects of such storms has been felt with peculiar force, these demands have been met by the British government in the laying of an emergency telegraph cable between London and North Britain. The fact that such unanimous demands are made for the prevention of even a temporary loss of the telegraph between important centers is, it may be remarked, a rather notable acknowledgement of the indispensibility of this public utility as a part of the commercial and social structure of a country.

Apart from the very important matter of maintaining uninterrupted telegraphic communication regardless of weather conditions in the interests of the general public it may safely be assumed that the various telegraph authorities in this country have not been unmindful of the financial losses sustained by the telegraph upon the occasion of each recurring collapse of poles and wires, and that every possible remedy therefor has been most carefully considered. Furthermore, telegraph lines are not only subject to widespread damage from abnormally severe sleet and snow storms, but are also in many places exposed to the ravages of forest fires, avalanches of snow, washouts due to floods, and to destruction by lightning. Again the average life of a pole line in all parts of the country probably does not much exceed ten years. Consequently, if the financial and engineering difficulties in the way of placing telegraph wires underground on a large scale had not been practically insurmountable, that solution of the problem, unquestionably, would have been long ago adopted. But it is well known, for instance, that the increased static capacity and mutual induction of the conductors carried in cables tend to reduce very materially the length of circuit that may be used in satisfactory telegraph operation. Already indeed the presence of a comparatively limited amount of underground cable in the circuits passing through the principal cities of this country has reduced very preceptibly the speed of signaling and the general efficiency of automatic and multiplex telegraph circuits in this country. Being therefore aware of the great technical and financial difficulties that would attend the placing of wires underground generally between cities and towns over the expansive territory of this country, the question of building stronger pole lines, and of employing larger and stronger wires has been frequently proposed by telegraph engineers. The well known " A " and " H " methods of setting wooden poles of course have received due consideration, and in trials have been found to add considerably to the stability of lines. In addition however to doubling the expense for poles, further objection to the use of these methods, especially where the telegraph lines are on a railroad right of way, is the extra space required for setting, which very often is not obtainable. Another plan tested was that of using worn out track rails, set up in " H " form and braced one foot apart. The cost of setting these rails is, however, rather high, being about eleven dollars per unit. In especially exposed places the plan of doubling the number of poles from say 50 to 100 per mile, has been adopted with considerable success. A reduction of the height of poles and an increase of their girth has also been advocated and there is now a tendency in that direction. It is very probable that pole lines built in the future will when possible be built of poles considerably less than 35 feet in height (the present general practice) with head and side guys located about every half mile regardless of the contour of the line. On heavy loaded lines with the poles set about 100 feet apart reduction of the leverage obviously increases the efficiency of guying. In the construction of a thirty-wire line by using ten-pin cross arms a 25-foot pole would generally leave sufficient clearance.

The employment of re-inforced concrete poles for telegraph purposes has been suggested as offering a solution of the problem as regards durability and reliability[27] but has not gained much headway hitherto, principally owing to the present high cost of such poles and also to the excessive cost of transportation. Even, however, if experience should show that cement poles will possess the ability to withstand the strains brought to bear on them by wires heavily coated with sleet, there still remains the unfortunate fact that the wires themselves may break under the strain. It would of course, be a decided gain to avoid the total loss of miles of pole line by the collapse of the poles like bricks in a row—a not infrequent occurrence under present conditions.

In relation to the immediately foregoing remarks, it may not be amiss to digress here to suggest that since the telegraph lines are not put up merely for a day or a year, that a combination of concrete poles, or towers of equal strength and durability with perhaps some form of housing for the wires along permanent and isolated rights of way may be among the possibilities of future telegraph engineering, since such a plan offers promise of reliability of operation without the detrimental accompaniment of impaired efficiency of the telegraph service that follows the placing of telegraph conductors underground. In view of the importance of the subject further reference may here be made to the reduced efficiency of quadruplex telegraph operation within recent years, in some cases amount-

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27. (See paper by Mr. G. A. Cellar, " Experiments with Concrete Poles" Proceedings, Association of Railway Telegraph Superintendents, 1907, p. 144)

ing to 50 per cent, due to the increased amount of telegraph conductors placed underground in cables in cities. In other cases certain quadruplex circuits have been abandoned because of inductive disturbances from parallel high tension transmission lines. It is a well established fact that prior to the introduction of these disturbing factors, duplex and quadruplex telegraphy in this country had attained a high degree of efficiency. Thus, for instance, it was formerly common practice to operate four, six or more quadruplex circuits between New York and Boston on open parallel lines, each with an efficiency equivalent to four wires worked simplex, and certain quadruplex circuits between New York and Chicago were operated as a rule with an efficiency of at least 90 per cent.

In the equipment of the quadruplex circuits to which special reference is now made, the ordinary horse-shoe polarized relay, with flat armature, and short cored neutral relay were employed without any devices to aid the operation of the No. 2 side excepting the Edison device of the back contact and repeating sounder attachment to the neutral relay. It is well known also that in isolated sections at the present time quadruplex circuits are still operative at high efficiency. It would appear evident therefore that a restoration of the original efficiency of this exceedingly important arm of the telegraph service would be alone an aim worth the best effort and thoughts of telegraph engineers and executives. A return to the former or greater freedom from inductive disturbances would also vastly enhance the opportunities for the utilization of some of the readily available rapid automatic telegraph systems, which as previously intimated the introduction of night letter telegram service may render imperatively necessary in the very near future.

Returning briefly to a consideration of the matter of obtaining a permanent, non-inductive, non-retarding system of telegraph routes, it is clear that utilizing the suggested towers or reinforced concrete poles, with housed wires to afford mechanical protection against storms, incidentally thereby guarding against undue variations of insulation resistance, (a great desideratum for numerous reasons) and by the proper selection of routes at a suitable distance from high-tension lines thus evading their disturbing inductive currents, an immediate improvement in the operation of circuits would be obtained. There would, however, still remain to be dealt with, the detrimental effects due to the presence of conductors in underground cables leading into and out of cities and towns. This difficulty could, however, be obviated by placing the main operating departments of telegraph offices on the outskirts of such cities, from which offices loops might be run from duplex and quadruplex circuits to the various branch and brokers officers without detriment to the operation of the multiplex main circuits. All wires not required for the actual handling of traffic in a given town would in such cases enter the main operating room on the outskirts of the city and pass on without entering the city proper. In many small towns the telegraph lines following the highways enter at one end of the town and pass out at the other end, a custom that has frequently involved placing a comparatively large amount of cable in an unimportant locality considered from a telegraphic standpoint. By the plan suggested, only wires needed locally would enter the place and that by the shortest route to the business center, thereby minimizing the amount of cable required for the proper transaction of telegraph business at that point.

It is unnecessary here to comment on the economies and improvement of operation that could be rendered possible by even a partial adoption of the foregoing suggestions, further than to remark that a proper consideration of the subject will show them to be manifold and of great value.

It had been intended to include in this paper a general reference to recent improvements in the interior equipments of telegraph offices and also to describe the methods and materials now employed in aerial and underground telegraph cable work in this country, but owing to the brief time available for the preparation of the paper it has not been practicable to carry out that intention.

DISCUSSION ON "AMERICAN TELEGRAPH ENGINEERING—NOTES ON HISTORY AND PRACTICE." JEFFERSON, N. H., JUNE 29, 1910.

W. Maver Jr.: I should like to say that this resume is not by any means a full account of the history of American Telegraph Engineering. For instance, in the paper nothing whatever is said about lightning arresters, the forerunners of the switches of which we heard so much this morning. The early telegraph engineers had their troubles with lightning, and the methods adopted to overcome these troubles were numerous; finally coming to the method which is in universal operation to-day, that is, the short path to earth for the lightning current.

About twenty-five or thirty years ago the electric light was inaugurated, following which very quickly telegraph companies began to be troubled a good deal with crosses between the wires of the two systems, with the result that the telegraph switchboards were often burned out, and not the switchboards only, but the buildings of the telegraph companies also. To obviate these troubles as much as possible, the method was employed of coiling up fine German silver wire into coils the size of a pencil, consisting of ten or fifteen turns termed the spider wire. This was put in series with these telegraph circuits at the switchboard, in addition to the short air gap arrester. I do not think the engineers had any thought at the time that the coiling of the wire would have any effect in retarding the progress of the oscillating current towards the instruments.

Ralph W. Pope: The introduction of the Morse telegraph system was followed by what purported to be improvements, and many of these improvements have practically passed out of existence. I refer more especially to the House and Hughes, and the "combination" printers, which followed, leading off with the House printer in 1847 and 1848. I was familiar with the work of that printing instrument, although I did not operate it. My printing telegraph work was confined to the Hughes printer, which was introduced, as you may say, experimentally in 1858, although it did not come into general service. The "combination" printer, so-called from the combining of certain features of the House and Hughes printers by the late George M. Phelps, was, however, used on important circuits by the American Telegraph Company a little later.

One of the defects of the House printer, which was an ingenious machine, was the limited distance over which it would operate, and I would call the attention of the author of the paper presented to the possibility of an error in regard to this having been operated on lines 1,000 miles in length. While that might be true, in a sense, as a matter of fact it was not usually operated between New York and Boston a distance of perhaps 225 miles, except in very fine weather. The ordinary practice was to repeat at Springfield, which was about half way.

One of the difficulties of the early printers in regard to their general adoption was their failure to meet the requirements for way-station work. This was met in the case of the House printer, as is not generally known, by the use of a simplified form of the printer. As the type wheel stopped, the exposed letters could be followed by an expert operator without the use of the printing device. A simpler form was introduced which operated as a dial printer, the operator reading from the wheel, instead of the printing mechanism being used to print on the tape. That was one of the reasons why these earlier types of printers were not successful commercially, for the reason that they could not be used in many stations on account of the expensive equipment.

The question of high speed and the use of the chemical telegraph created considerable interest in telegraph circles at the stage referred to by the author. It is interesting to note that in one of the important experiments made, which is referred to in this paper, that the time consumed in perforating, in transmitting and translating, was more than would have been required by four Morse operators in transmitting the President's message referred to, a difference between seventy-two minutes as against fifty-two minutes. The use of the chemical system raised so many objections that it is not strange it went out of use, but it was at one time quite successfully established in New England, but not using the perforated tape, simply hand transmission, the same as with the Morse system.

The improvements in the Morse telegraph have been largely due to the increased skill of the operators. The use of the typewriter, which has been referred to, brings to mind a rather peculiar relation between the rapidity of transmission by hand and the rapidity with which the operator could receive the same message with a pen. They kept hand and hand, or rather neck and neck, for years, until by the introduction of the typewriter, the receiving operator could copy much faster than the sending operator could send by hand, and this has led to the use of a code for press dispatches, which standardized abbreviations, but the use of the code is not permissible in ordinary private messages, and for this reason the typewriter is still ahead. When we consider the adoption of the mecograph, as it is called here, by the Morse operator for improving the rapidity of his sending, it appears quite possible that the introduction of the Continental code may be brought about some day, as it would require less time, perhaps, to learn to operate by the Continental code used in the wireless system, than it does to learn to operate by these mechanical devices.

The improvements in insulation to my mind have not been so great as the improvements in the conductivity of the line. The early lines, as I recall, used No. 8 iron wire, and then No. 9, and with the introduction of the duplex and quadruplex, as referred to by the author, wires of greater conductivity were introduced. The form of glass insulator now used has persisted for about thirty or forty years.

The possibility of the utilization of a more rapid system, with the introduction of the night lettergram practice, appears to be quite possible. I have talked with some of the telegraph men about that, but they do not see any probability of it yet. It must, however, take the form, in order to be practicable, of some system of perforation like the Barclay printer which transmits with only one repetition, that is, the perforation producing at the other end a page printed telegraph blank. It is rather remarkable that, although the objections to the form of printing tape were so well known in the early days, there appears to have been no attempt to bring about the introduction of a page printing system. When we consider the ingenuity of those early inventors, House and Hughes, it seems to-day as though, if their attention had been directed to this defect, that they might have invented a page printer, and thus perhaps prolonged the life of the printing telegraph system, which has practically gone out of use.

John B. Taylor: Delivering a telegraph message from a person in one part of the country to a person in another part of the country involves something more than getting a code of signals over a given wire. It involves "readiness to serve" at all hours of the day and night, frequently in small places only during certain hours of the day, and also a system of collecting and delivering messages. This, as far as I can see, is the main reason why automatic systems, which can send signals over the wire at a phenomenal rate of speed, sufficient to give a thousand or more words per minute have gone into use only in very limited cases. Mr. Maver can, I hope, enlarge on this point. We see frequently the statement that the telegraph people are not alive to the possibilities of sending messages at a great rate of speed over a single wire, and while a number of messages over a single wire is a good thing, perhaps, between two large cities, it is of practically no use at all to the small towns, of which there are a great many in the country.

The telegraph line is rather apart from the work of many of the members of the Institute, so we are fortunate in having a paper giving an up-to-date resume of present practice. It is difficult for a man out of the field to know just what is being done. The old books give descriptions of duplex systems, quadruplex systems, repeater systems, etc., which are all interesting, but help little towards a knowledge of present practice in the majority of cases.

My own renewed interest in telegraph and telephone matters has been due to the disturbance feature from power lines, and one or two points occurred to me as Mr. Maver was abstracting his paper. It is plainly brought out by him that the practice of quadruplexing, (which means four messages over a single wire at the same time), was not worked to an extent, which, at first sight, it would seem that it should be. This is due to a number of reasons, possibly divided up between poor insulation, variable weather conditions, etc., and to a large extent due to inductive disturbances and to circuits of the same class on the same pole line. This raises the question whether the telegraph companies could not afford to use metallic circuits, in which case the matter of inductive disturbances from their own wires, as well as foreign wires, would be obviated. The matter of insulation would still, perhaps, be troublesome, but this could be improved without an investment which would be very great, in comparison with the investment in poles, wires, etc.

There is also the possibility of obtaining greater capacity from present wires by the combined telephone and telegraph systems. If the demand for telegraph wires and the demand for telephone wires comes out in a certain ratio, we might have metallic circuits between all the important points working as telephone wires and also perhaps a sufficient number to take care of telegraph service, some as grounded lines and some as metallic lines phantomed between two pairs of telephone wires. The curve of demand probably varies to a great extent, the telegraph business of a certain sort going out in the daytime, probably at the peak of the telephone load. With the introduction of the night lettergram, at day rate at a time when the wires are probably not very busy for telephone work, (at any rate since the night telephone rate has been abolished) it is to be hoped a more economical working of the conductors will result.

I did not have time to look the paper over very carefully, and do not know just what Mr. Maver said about the Rowland system, which a few years ago was written up in an Institute paper by Mr. Potts, I believe, where an octoplex capacity was claimed for it. This system used the page printing device direct from keyboard to the message blank for delivery at the other end. I have not heard lately of any extensions made with it, and if Mr. Maver can say a word or two as to the general reasons for the apparent inactivity, I should like to hear from him.

Incidentally, my name has perhaps been taken in a way to give me more credit than is due. In the paper reference is made to the New York, New Haven and Hartford Railroad Company, and also to Fig. 10 which carries my name. Although interested in the work on the New York, New Haven and Hartford Railroad, for the Western Union Telegraph Company, I did not originate the general scheme of neutralizing induction action. This arrangement used was devised by engineers of the Westinghouse Co.

Gano Dunn: I heard Mr. Maver say that four-fifths of the operators in this country use the Martin mecograph. Is this really so?

My observation as I travel around the country is that we do not see many of them, although I do not get into the central offices.

I have found them imperfect, probably because of my own lack of skill, but there seemed also to be certain inherent difficulties such as difficulty of adjustment and not enough certainty of action to cause all the dots to go through on a long and variable line.

It is also difficult constantly to change the adjustment of the mecograph to follow the rising and falling inductive and leakage changes that are found on a long and poorly constructed line, with many stations.

The wireless telegraph is introducing a greater than ever conflict between the Continental and American Morse alphabet. I should like to know whether there is any attempt towards a more general introduction of Continental Morse into this country, and if so, what Mr. Maver thinks of its probable success.

William B. Hale: Perhaps a few remarks on the telegraph system of the Republic of Mexico may not be amiss. The system there is an extensive one, considering the comparatively few large centers of population. The telegraph lines extend to even the smallest towns and villages, because, being a telegraph controlled by the Government, its operation is not based upon the question of profit. The Government is ready and anxious to install a telegraph office in any town which has any need for such service, whether it will pay or not. The idea is to supply reliable telegraph service to the entire people at cost.

The general equipment of the system is practically that of the United States of a few years ago. The Morse manual system, with simplex, duplex and quadruplex operation, is in use; and the lines are mainly constructed with No. 8 galvanized iron wire and a European type of porcelain insulator. Wooden poles are chiefly used, but some of the trunk lines have iron poles. There are a few Hughes printers in service in the Capital for communication between the central office and its branches. In the larger cities of the country duplex and quadruplex instruments are used, and in all other offices the Morse simplex is employed. The American closed-circuit system of operation is in use; also the regular Morse alphabet, with a few changes to adapt it to the Spanish language.

The telegraph is used very extensively in Mexico, not only for business purposes, but for social and personal matters as well. To a very considerable degree the Mexican makes use of the telegram where you would the mail, or a messenger service. He sends telegrams from his place of business to his home, messages of congratulation to friends on their birthdays and telegrams of felicitation on such days as Christmas and New Year's. In the City of Mexico one finds a very convenient form of service for such social messages; we have a card, about the size and shape of your postal card, which can be purchased for five cents, Mexican currency, the equivalent to two and one-half cents in your money. On the front of the card is a space reserved for the address and a number of ruled lines for the message, which must not exceed ten words. These card-telegrams, after being filled out, may be deposited in boxes, similar in appearance to letter-boxes, which are placed at the more important street corners throughout the city, and from which frequent collections are made. The messages thus collected are delivered at the nearest branch office, telegraphed to the office which is within the shortest distance of the person to whom they are addressed, and from there delivered by the regular messengers. This is a prompt and efficient, as well as cheap, means of communication within the limits of the Federal District—in the center of which lies the City of Mexico—and it is very extensively employed for business and social purposes.

The rates for telegraph service in the Republic of Mexico are low. A ten-word telegram may be sent from one end of the country to the other for only one peso, or fifty cents in American currency. The rate for night messages, which are transmitted from 10 o'clock in the evening until midnight, is one-half that of the day rate.

We have been unable to use copper wire for pole lines to any extent, for the reason that it is cut down and stolen by the *peones*—the lower-class natives. Iron wire has so far been employed almost exclusively for the construction of pole lines, but I have suggested the use of a steel core copper-clad wire, which will improve the service and will probably not be stolen, as when cut down it will have very little, if any, value as scrap metal. This copper-clad wire will undoubtedly remain up, and it ought to prove especially valuable in a tropical country like Mexico, where even galvanizing does not protect iron wire from corrosion for any great length of time.

The success of the Federal Telegraph System of Mexico would lead one to favor a government-controlled telegraph. The service is rendered at rates much below those which would be charged by a private corporation; and the dispatch of telegrams is in every respect satisfactory, being prompt, efficient and thoroughly reliable.

G. A. Cellar: The employment of reinforced concrete poles for telegraph purposes has not gained much headway hitherto, in this country. I believe the reason to be principally because of the still comparatively low cost of wooden poles, and the lessened expense of handling the latter as compared with that of handling concrete structures. In Europe, however, reinforced concrete masts are more largely used than in this country. The Deutsche Schleuderrchren-Werke has been making hollow concrete poles by machinery, utilizing centrifugal force, for about five years, and with a great deal of success. The Siegwart company about a year ago completed at its Swiss factory a contract for several thousands of hollow poles, averaging forty feet in height, for power lines, constructed by machinery utilizing centrifugal force. My information is that throughout Western Europe, especially Germany, Switzerland and France, and to perhaps a lesser extent in England, concrete poles are now considerably used in place of timber.

Until the time arrives when a permanent location can be secured for a telegraph line—and a telegraph line of large capacity—it may not pay to build an open line of wires supported by high concrete poles, unless their cost shall but slightly exceed that of wooden poles, for several reasons, among which are; first, possibility that the low voltage signaling systems now in vogue may be forced underground, or somewhere beyond the present up-in-the-air location, by the multiplication of electric transmission lines; and, second, by the discovery of a process through which the elimination of retardation in aerial cables may be effected.

I believe that the increase in price of timber, and the advanced cost of handling concrete poles, will result in a revolution in the heretofore accepted models of pole and wire lines, through which there will be evolved a system of short pole lines of either timber or concrete, where reasonably level ground and policing arrangements permit the maintenance of such lines, and for which proper overhead crossings of highways and private roads encountered can be made without grading up and down from each one. It will not be feasible, however, to use extremely short poles in lines traversing rugged country and especially on railroad lines where the undulations of the surface of the ground are frequent and abrupt and the right of way a succession of deep cuts and high fills. Such lines are better calculated for use on highways where the roadway more nearly follows the form of the ground's surface and the ups and downs are not so abrupt. The objection to the use of the very short poles in the lines above indicated is that the vertical pull on the pins and insulators is certain to loosen the contacts with the supports and foster wire troubles in a degree not comparable with the saving in the lessened cost of the line. There is, however, a very considerable expanse of territory in this country in which the use of the short pole line is certainly feasible and desirable, not only through its lessened cost as compared with a line of high poles, but through its lessened exposure to wind pressure and the lessened strain at the ground line in a short pole as compared with a long pole. I am quite sure that for a comparatively small number of wires, a plan of construction can be evolved which will enable the large utilization of short pole lines with, perhaps, dead ended sections where it is necessary to abruptly raise the line in order to carry the wires over road crossings.

The item set forth in the paper as to the housing of insulators is one which I feel will be beneficial in many storms. No doubt the time will come when the expense incidental to such an installation will be more than warranted by the benefit thus to be derived. However, the driving storms of rain, wet snow and sleet which we experience in our western country preclude the entire protection from such storms by any small roofing protection that I think of at the moment.

Louis M. Potts: The authors make the following statement:

> It has long been recognized by telegraph authorities that an ideal system of telegraphy would be a simple and reliable page printer, capable of transmitting and receiving, say from 500 to 1000 words per minute on circuits of from 200 to 1000 miles in length.

This statement is not in accord with my understanding of the requirements demanded by practical men as far as such statements have been made. While it is possibly desirable in some cases that the ideal printer system should be capable of transmitting from 600 to 1000 words over a circuit yet in the great majority of cases the universal printer system would certainly be used at a very much less capacity than this. I take it that this statement of the authors does not necessarily mean a single mechanism to operate at this speed but apparatus capable of giving this capacity to a circuit. A single printer to operate at such a speed as this would certainly involve complications of construction and adjustment such as to preclude its use on short circuits requiring a speed of not more than 40 to 50 words per minute. I suggest that the ideal printer would not be a single printer capable of transmitting and receiving 300 to 500 words per minute each way, but that it would be a printer mechanism capable of operating at such a speed that the number of telegrams handled by the printer is that number of telegrams which can be economically and efficiently handled by a single operator. In a printing system with automatic transmission this number is determined by the capacity of the receiving operator rather than of the sending operator. Of course how many a single operator can handle depends very largely on the accuracy of the system and the traffic handling methods adopted, but from the present state of development of printing telegraphs it would appear that a printer system, manual or automatic, operating somewhere around 50 to 75 words per minute gives an amount of traffic which can be economically and efficiently handled by a single operator. A manual operator does not require a machine of a speed greater than 50 to 60 words per minute. The average operator could not send faster than this whatever the speed of the machine. In an automatic system a machine speed of 75 words per minute should give a sustained rate of about two telegrams per minute. A receiving operator will be fully occupied with this amount of traffic to care for. The operation of a number of printers of moderate speed on a single wire by some method of multiplex operation appears to meet the conditions imposed by those circuits requiring a high capacity machine better than a single printer of high speed. The use of a moderate speed printer makes possible the construction of a simple, cheap and reliable printer which will be suitable for use on circuits having light traffic. This method of treating the problem results in a universal telegraphic printer, and a variation of the methods of line operation only, to meet the different conditions of traffic.

When a certain rate of transmission is reached on any given circuit, the wire cost is reduced to such a low figure that a further increase of rate is not justified, as the further reduction of wire cost so obtained will be more than offset by the more frequent interruptions and the greater amount of supervision required.

If such a system as the authors suggest, as far as the mechanism is concerned, were in a perfect state of development, I do not believe that it could be successfully operated on the wire plant of to-day on account of the variable electrical state of the wires, the lack of protection against inductive disturbances from foreign sources and a method of construction which also lacks protection against the induction between the different wires on the same pole line, which makes impossible the use of extremely high speed telegraph apparatus on more than a few wires, and which materially reduces the efficiency of even the Morse manual system. In order that a printer system operating at a speed even approaching 600 to 1000 words per minute may come into use it is just as important that the wire plant be perfected as the machine itself.

W. J. Camp: I would say that the Canadian Pacific Railway used white porcelain insulators to a considerable extent in the years 1890 to 1898, but the cost increased so much that we reverted entirely to glass until three years ago. We found that the manufacture of glass insulators in Canada had deteriorated so greatly that the insulators turned out were altogether unsatisfactory, apparently they were not properly annealed, with the result that from a week to two months after being placed on the line they would go to pieces without being subjected to any mechanical injury. The price of porcelain insulators had also been so much reduced that for the past three years we have used nothing but white porcelain.

Relative to Wheatstone Automatic operation it may be noted that the British Pacific Cable Board has leased a wire from the Canadian Pacific Railway between Montreal and Vancouver and is now equipping this wire with that system.

The Canadian Pacific Railway method for indicating circuits was adapted from the Japanese system and is by small circles at the ends of straight lines, different markings appearing in these circles as follows:

○ Commercial Simplex.
⦶ Duplex.
⊗ Quad.
● Despatcher Simplex.
◉ Simplex leased.
⧗ Composite, Simplex and Telephone.

I consider a line of 40 poles per mile to be the most satisfactory provided that poles are side guyed varying from every 5th or every 20th poles according to danger from storms, and head guyed every half mile. I do not like increasing the number of poles to more than 40 because, besides costing so much more for construction there is also greater reduction in insulation of the wires.

F. W. Jones: In addition to the historical and descriptive parts of the paper, allusion is made to disadvantages and defects in the construction of lines and in the operation of electrical systems of transmission, and suggestions for their improvement are advanced. Any ideal construction of telegraph lines, and the employment of the most improved and speedy systems for the transmission of telegrams must inevitably be limited in cost to the capital that can be secured therefor, and engineering suggestions of any value must keep within the limits of practicability, which is determined by several considerations, probably better known to the presidents and general managers of telegraph and railroad companies, as those officers are charged with the success and financial results of operation and maintenance, and are de-facto the engineers who decide all questions involved.

That those officers have been able to attain their ideals in these matters is extremely doubtful.

Capital is discouraged by the enormous difficulties encountered in the upkeep and extension of our American telegraph system, such for instance as securing suitable rights-of-way for trunk lines, with their constant demand for added wires; the frequent attempts in Congress to inaugurate a government system; the unfavorable legislation and taxation of the various states; the encroachment of the use of telephones and wireless telegraphy, not to mention the competition of a splendid mail service, besides the increasing cost of labor and materials, and the rigid account to which the proprietors are held by the Courts, for errors and delays which are practically impossible to avoid. Up to the present time the Morse Telegraph system has withstood the inroads of telephone and mail competition, and continues to be favored with an increasing patronage.

The grave situations in which both proprietors and public are placed by the present inability to obviate interruptions to operation between commercial cities, by reason of breakdown of wires and poles, due to storms, fires, floods, snow avalanches falling trees, etc., besides the detrimental effects of electromagnetic and electrostatic induction upon the signals, are not confined to any one company, and their free discussion seems to be well within the purview of the Institute and cannot reasonably be considered gratuitous by telegraph proprietors. In my opinion there are insurmountable financial and engineering obstacles to placing entirely underground the trunk lines between all of the widely separated cities of this continent, except that emergency underground cables may be found an advantage for short distances such as between New York and Philadelphia (90 miles), yet an overhead structure that would be more elastic, built under rigid engineering rules as to strength, number of supports per mile, gauge and number of wires or cables, etc., with reference to the character of the country traversed, and the maximum stresses, (short of cyclones), to which such structure would probably be exposed, could undoubtedly be built at less cost than an adequate and reliable underground system. Upon engineers will devolve the solution of very important questions such as the proper tensile strength of the wires; their ohmic resistance; character of the insulation; and whether open individual wires, or cables be employed. It is obvious that the suggestions in the valuable paper of Messrs. Maver and McNicol, as to the kind and number of poles per mile, are indefinite. As there are great differences of topography and climate to be encountered, different construction is necessary for lines crossing mountains, prairies, mesas of shifting sand, through canyons subject to cloud bursts, and forests where trees are frequently falling, also along the sea coast indented by rivers and bays, and through the latitude where sleet storms frequently visit. A heavy trunk line in northern latitudes would require considerably different construction from a light trunk line in the south. The annual reports of telegraph companies show an expenditure of many millions of dollars for the repair and maintenance of pole lines.

It is open to engineers to calculate what would be the saving in electric operation, if the conductivity, and consequent tensile strength, were very largely increased over that of the wires at present employed overland. I believe that an increase of at least 50 per cent in the conductivity of the largest hard drawn copper wires now in use, would much more than compensate for their additional first cost, but of course they must be supported by the ideal structure above referred to.[1] The average life of a pole line is given as 10 years, this may be true of wooden poles, but not of crossarms, insulators, nor wires.

It has generally been the opinion of engineers, that to secure reliable telegraph lines between the Atlantic and Pacific, over the Rocky Mountains in northern latitudes, that it was necessary to have the protection of the railroad tunnels and snow sheds. The recent construction of a portion of an important trunk line over the summit of the Sierra Nevada Mountains, will be watched by engineers with interest.

A very vital question to be decided in erecting an ideal line, is the kind and gauge of wire best suited for both trunk and side or way lines, also whether iron, or aluminum, or other metals or compounds could be advantageously used instead of hard drawn copper, in case the cost of the latter became excessively high.

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[1] *Elec. World & Engineer*, March 29th, 1902, page 557. *Telegraph Age*, Nov. 1, 1903, page 540.

The voltage of signaling currents at present in use, particularly for quadruplex, duplex, printer and fast Morse key operation, is at its maximum limits, on account of the detrimental sparks at the contact points of transmitters and of the heating of bobbins of relays, and of the serious menace to the insulation of office wires and underground and river cables.

The increased speed of signals within the last twenty five years, particularly by the use of mechanical transmitters, and by the rapid electrical impulses required for printing and automatic systems on long circuits of comparatively high resistance, has demanded the highest voltages that could be used in order to actuate the relay armatures with sufficient force and celerity.

The mecograph illustrated in the article has a lever that may be moved by a slight motion, from a central or open position, to the right to transmit dots, and to the left for dashes; and is operated by about 30 per cent fewer motions of the hand than is the case with the Morse key, but the motions of the mecograph being lateral instead of vertical, afford relief to the operators muscles that had grown tired from long use of the Morse key.[2]

The Wheatstone automatic system has been employed for several years on the long ocean cables, and on overland wires between London and Persia, and has produced more rapid and reliable signals, increasing the carrying capacity of the cables and wires by obviating the loss of time due to the hesitation of key operators in reading copy, and to other causes. Thus changing the cable transmission of business from *intermittent*, to *continuous*.

Repeaters are placed anywhere from 250 miles to 600 miles apart in circuits having very widely separated terminal stations. Such repeaters have their location determined by the convenient position enroute, of a town or city best suited for the maintenance of operators and machinery and not by the object of securing the best conditions for the electrical operation of the wires. The use of quadruplexes is most seriously curtailed by the false signals produced on the neutral relays when the keys on number two sides of several sets in operation on adjacent wires are simultaneously closed, which frequently occurs, the resultant electrostatic induction is then at a maximum.

It is to be hoped that the "ideal system of telegraph authorities in this country" capable of transmitting and printing from 600 to 1000 words per minute on long wires will not lead any of our bright ambitious young engineers to chase an *ignis fatuus*. I am at a loss to understand why the limit was not placed at at least 5000 words. It is obvious that the time-constant of all known line wires, electromagnets, and their connections, for over 200 miles, when operated by the very highest permissible voltage, would absolutely fail to actuate any page

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2. *Telegraph Age*, July 16, 1906, page 325.

printing mechanism at such a speed; it is just as sensible for railroad engineers to ask for a locomotive and cars to carry passengers from New York to Chicago in one hour's time, upon present tracks.

This ideal system must be required for press or similar service where the message contains several hundreds of words, and is prepared in some way for continuous transmission, on its being placed in the machine at the sending end. It is impossible for me to imagine how individual telegrams of an average of 30 words each can be prepared in any manner to be continuously transmitted over a wire at the rate of 33 messages per minute. At the time of Mr. C. F. Varleys visit, and of the subsequent modification of relay resistances by Madison Buell, comparatively nothing was known in the United States of farads, and henrys. It seems that our engineers were then trying to secure the maximum magnetic pull on relay armatures with a minimum electromotive force, and overlooked the tardy action of the apparatus due to high inductance. The adoption of a standard of 150 ohms for single relays was due to the impossibility of a large telegraph company regulating the resistance to suit each circuit. The late W. W. Smith in patent No. 106,418 in 1870 claimed the multiple connection of a 150-ohm relay to the reduced resistance of 37½ ohms, he found such relays were not so sluggish in action on a wire equipped with a large number of relays, as were the same number of 150-ohm relays, the improvement was one of better service, and not of decreased cost for current.[3]

Donald McNicol: Mr. Jones questions the likelihood of the development of a printer system capable of transmitting 600 words per mintue over ordinary circuits. That one cannot readily conceive of the probability of such speeds being attained, is probably due to the fact that he confines his speculations regarding mechanical operations and movements, to what it has been possible to accomplish in the past by means of electromagnets.

The KR limitations of circuits (including lines, and windings of instruments) where such circuits are spaced into repeater sections of approximately 500 miles, are in the case of aerial lines, of such consequence, that with ordinary voltages, with lines worked duplex; speeds of 300 words per minute are about as high as is possible where the operations are dependent upon electromagnetic control. There is one printer system in use in Europe for which a speed of 350 words per minute is claimed.

It would be, as Mr. Potts implies, a highly desirable feature of a universal printer telegraph system if its operating capacity were as elastic as is the telegraphic traffic in volume on any given circuit, provided, of course, that its general application to circuits having varying loads at different periods of the day, would permit of economical operation as compared with Morse methods, when the volume of traffic is far below that of the maximum capacity of the machine. Flexibility of operating capacity, with a high maximum rate, would serve to take care of varying loads and of the accumulations of traffic due to temporary loss of wires.

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[3] *Telegraph Age*, Sept. 1, 1902, page 382. *Telegraph Age*, Oct. 16, 1902, page 438. *Telegraph Age*, Nov. 16, 1902, page 476.

With reference to Mr. Jones remarks dealing with the fate of the engineer's recommendations.

The practical engineer realizes that even in the reconnaisance stage any engineering proposition must be worked out with practicability and economy as factors. Even if for temporary considerations an engineering proposition may not be adopted, it still remains that by virtue of the thought and effort devoted to its development, the proposition will survive as a basis for future undertakings along the same lines. Naturally where the engineer is a traffic economist he has given due thought to the requirement that any proposition he may submit calling for the outlay of comparatively large sums of money for new or for additional equipment, must provide for economical results, or in some manner for enhanced advantages over the methods it is intended to improve, which will insure adequate return on the investment. Although the live engineer is professionally zealous, his conservatism would seem to be well established by virtue of the fact that the major number of the propositions submitted to him for investigation are found to be and reported as impracticable or unprofitable.

W. Maver Jr.: The President is very desirous of getting to the other matters scheduled for the program this evening, and I shall therefore at present only say a few words in reply to the points brought out in the discussion.

Mr. Pope queries the statement that places the distance of transmission by the House printer at 1,000 miles. The statement is traceable to the officers of the original House telegraph company and may be found in "Electric Telegraph," Jones, 1852, page 112, as follows: "The longest line we have is about 1,000 miles—extending from New York to Cincinnati. Messages are transmitted that distance with ease; and no doubt we shall be able to telegraph direct from New York to St. Louis as soon as our line, now building, is completed." Possibly the discrepancy between this statement and Mr. Pope's experience may be explained by a superior conductivity of the newly constructed wires in 1852 as compared with the wires of Mr. Pope's time. It was the common experience of those days, 1865-1870, that, owing to the manner of making joints then in vogue, (a simple twisting of the ends of the wire without solder), the resistance at the joints in a few years almost amounted to a break in the continuity of the wires. For instance, one of the New York-Bridgeport wires tested by Mr. Varley and mentioned in his report (see page 1289) showed it to have a resistance of 241 ohms per mile—normal resistance 13 ohms per mile.

In regard to early attempts to produce a page printing telegraph it may be noted that Charles Wheatstone, about 1840, devised a page printer telegraph system, but it was rather slow and did not get into general operation. Described Sci. Am., May 31, 1884.

Mr. Taylor expresses the opinion that some of the present trouble on multiple telegraph circuits is due to the mutual induction between parallel wires. About twenty years ago I had a very large experience in the practical operation of multiplex telegraph circuits while I was the electrical engineer of a large telegraph company in this country, and the statements on this point in the paper are based upon that experience—we operated circuits between New York and Boston, five or six quadruplex circuits on parallel wires at top speed, obtaining an efficiency virtually of one hundred per cent, except in very bad weather. I found, that when we already had five or six parallel quadruplex circuits, the imposition of additional circuits did not have any detrimental effect upon the operation of the others. Hence, I feel safe in saying what is said in the paper—if it were possible to get rid of the stretches of underground cable and the inductive disturbances from high tension transmission circuits, it would be possible to restore the former conditions of multiplex operation.

The disuse of the Rowland printer in this country is probably due to a number of causes, chiefly perhaps the somewhat complex nature of the apparatus and its unreliability at times. Mr. Taylor himself suggests some of the causes for the present non-use of high speed chemical automatic systems, to which it is assumed he refers, having the phenomenal speed capacity of 1000 words per minute. Numerous other causes have been cited at times without number by those who have had practical experience with such systems. It is pointed out in the paper that automatic systems capable of transmitting at the high speeds mentioned were in operation in this country 30 years ago and are still freely available when desired.

As to the statement relative to the extent of use of the vibroplex, mecograph, and similar instruments to which Mr. Dunn has referred, namely, that four-fifths of the operators now use such instruments, it may be said that investigation will probably confirm that statement. So far as the feasibility of transmitting speedily with this device is concerned, it can be stated that duplex circuits are being operated now between New York and San Francisco, with, I think, three sets of repeaters, by means of semi-automatic transmitters at the highest speed of manual Morse transmission.

Charles F. Scott: Is that repeating done automatically?

Mr. Maver: Yes, regular automatic repeaters, duplex repeaters. The method is described in the paper. The matter of displacing the spaced letter or American Morse alphabet as used in the United States and Canada, by the Continental Morse Alphabet has been proposed frequently within the past

50 years without result. There is no question that for manual sending the American Morse alphabet is the speedier, there being 214 time units in the American to 214 time units in the Continental, exclusive of numerals, and the liability to errors due to the spaced letters of the American Morse alphabet is minimized by the fact that the operators by habit almost universally exercise extra care in the transmission of words containing spaced letters. In automatic transmission, however, as by the Wheatstone system, the use of spaced letters is a source of delay as it is virtually necessary to double space words containing spaced letters in order to avoid errors. Thus the situation stands at present. Possibly the use of the Continental alphabet by wireless telegraph operators may assist in leading to the general disuse of the spaced letter alphabet.

Exception may be taken to Mr. Jones statement that the presidents and general managers of telegraph and railroad companies are de-facto the engineers who decide all questions involved. They may act adversely or favorably upon the reports of their engineers for financial or other reasons, but that does not constitute them the engineers of the company. Apropos of this may be quoted the following sentences from a recent paper by Mr. George Westinghouse*. "In view of the fact that there had been no considerable demonstration of the single-phase system by actual use, and that the New Haven trains would be obliged to operate upon twelve miles of lines already equipped with the direct-current third-rail system, it must be conceded that the directors and management of the New York, New Haven and Hartford Railroad showed great courage and confidence in the judgment of their experts." Mr. Jones is quite in accord with the authors of the present paper in expressing his opinion that the financial and engineering obstacles to placing entirely underground the trunk telegraph lines between all of the widely separated cities of this continent, etc.

Mr. Jones statement that the resultant electrostatic induction is a maximum when the keys on the No. 2 sides of several adjacent quadruplex sets are simultaneously closed will bear considerable qualification. For instance, there must be a particular coincidence of polarities to line on the No. 2 sides to bring about this maximum. One can easily conceive of a condition of complete neutralization of ill effects, depending on the polarities to line at a given instant, when all the No. 2 keys are closed. Furthermore, instances are cited in the paper in which many adjacent quadruplex sets have been operated without any impairment due to the cause stated.

Concerning Mr. Jones wonderment that the limit of transmission of an ideal printing telegraph system was not placed at 5000 words per minute, instead of 600 words per minute, the reason may be that the authors were desirous of keeping within limits that are at least eight times nearer attainment than Mr. Jones' system. Mr. Jones' arithmetic is perhaps astray in the computation that a transmission rate of 600 words per minute would involve preparing 30 word messages at the rate of 66 messages per minute. Twenty messages per minute is nearer the mark and twenty operators could easily prepare the messages at that rate. Mr. Jones seemingly bases his dictum that the time constant of all known line wires, electromagnets and their connections for over 200 miles would utterly prevent the operation of a printing telegraph system at the rate of 600 words per minute, upon the assumption that present methods must be strictly adhered to. This was not made a condition of an ideal printing telegraph system by the authors. The Buckingham-Barclay printer to-day has a capacity of 100 words per minute in each direction over circuits 1000 miles in length. In transmitting by this system each letter requires an average of nine time units made up of short and long pulsations of current of opposite polarities. The Murray printer of 150 to 180 words per minute employs five time units for the transmission of each letter. For the Creed printer, employing the Wheatstone alphabet, it is claimed that 225 words per minute may be transmitted.

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*A paper prepared for the joint meeting of the Am. Soc. M. E. and the Inst. M. E., London, July, 1910.

The Wheatstone automatic telegraph system which employs an electromagnetic ink recorder is capable of transmitting messages over regular telegraph wires at the rate of 600 words per minute, using the continental Morse alphabet, which requires an average of 8 time units per letter; the equivalent of 8 pulsations of minimum duration per letter. It is therefore perhaps not the time constant of the line or apparatus that stands in the way of a 600 word per minute printer so much as the present cumbersome methods of selecting the letter to be printed; together with the more or less cumbersome printing apparatus.

Hence it is conceivable that by the use of a method in which the time units required per letter may be halved or quartered the speed of transmission may be doubled or quadrupled without any change in the line or receiving apparatus, a result that would bring the speed of transmission quite close to if not beyond 600 words per minute. So in this respect as in some others Mr. Jones' railroad analogy is not as apt as at first sight it might appear to be. But the suggestion of an ideal printer telegraph as noted in the paper does not confine the prospective inventor to existing electro-mechanical apparatus. Photography and other physical agents controllable by electrical impulses are open to the ambitious and qualified inventor, who, however, could not say that the context of the paragraph in the paper relating to an ideal telegraph system conveys the impression that the realization of this ideal system is devoid of difficulties.

Mr. Cellar's remark relative to the housing of insulators indicates that he misses the suggestion of the paper that relates to the housing of the wires for mechanical protection against storms. Mr. Cellar's immediately following comment on the destruction of open wires by storms however emphasizes the said suggestion; as does also Mr. Jones mention of the annual expenditure of millions of dollars for the repair and maintenance of pole lines.

With reference to Mr. Pott's remarks concerning the impracticability of operation of high speed printing telegraph systems on wires subjected to severe inductive disturbances, it may be pointed out that a perusal of the paper will show that the authors are in strict accord with Mr. Pott's in this view.

It is noteworthy that many of the important inventions in mechanics and electricity have not been due to men directly engaged in the industrial application of those arts. Watt, for instance, was an astronomical and mathematical instrument maker. Morse was an artist by profession. Stearns, Bell and Pupin were not in the telegraph or telephone service when they produced their notable inventions in telegraphy and telephony respectively. Murray the inventor of the successful printing telegraph that bears his name was a journalist. Creed left the telegraph service to devote his time to the development of his ingenious punching and printing telegraph, and the list might be continued almost indefinitely.

One explanation of this fact may be that in the majority of cases the active engineers in an art are fully occupied with the successful operation of existing apparatus or with problems connected therewith, and are given neither the time nor the financial aid necessary to undertake original research for the advancement and betterment of the art with which they may be associated. Another explanation may be that in many cases the engineers in question are operating engineers, but not inventors. This suggests the question whether men thoroughly familiar with the requirements of telegraphy and of all the conditions to be met with in the technical telegraph service, and largely endowed with the inventive faculty might not be selected to prosecute investigations relative to the improvement of the telegraph service as relates to the transmission of messages, analogously as selected men in the medical and other professions and arts are now exclusively employed in matters relating to the advancement and improvement of those professions and arts.

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THE AUTOMATIC TELEPHONE IN RELATION TO CITY SERVICE.

BY ARTHUR BESSEY SMITH

The telephone requirements of a large city differ in certain essential points from those of a city of small or moderate size. The chief of these are as follows:

Measured service.

Private branch exchange service.

Interborough service.

Although these exist to some extent in smaller places, they are peculiarly important considerations in the telephone service of a large and congested city. They are practically the conditions which had to be met by the automatic telephone exchanges installed in Oakland and San Francisco, California. For this reason it is felt that a statement of the chief engineering problems of these cities and how they were solved will be of general interest.

The Setting. The interest in the region of the Golden Gate centers about two cities, San Francisco and Oakland. The former is a thriving seaport of about 350,000 inhabitants. It occupies the rough, hilly, northern end of the small peninsula (see Fig. 1) which separates the southern end of San Francisco bay from the Pacific ocean. The rather sandy region south of the city is thinly populated. The north peninsula across the Golden Gate is more thickly settled. To the eastward across the bay lies the city of Oakland, in the pleasant region between the Berkeley hills and the water. Oakland has a population of over 250,000 while Berkeley, Alameda and other smaller cities have about 60,000 inhabitants. The total population of the region reaches well up to three-quarters of a million.

San Francisco is a cosmopolitan city. There are Chinese, Italian and Latin quarters, each with its distinctive population and language. The wharves lie along the eastern edge of the city, with a great wholesale and manufacturing district south of the business center. Although a large amount of manufacturing is carried on, the harbor and shipping facilities have located the city and made it what it is.

Oakland has had a rapid growth since the earthquake across the bay and is second only to San Francisco in business importance. The cities are very closely bound together by business relations and also because so many business men of San Francisco live in Oakland. North of Oakland is Berkeley, the seat of the State University of California. Oakland also has considerable Chinese population, enough to warrant the serious attention of the telephone engineer.

Main office, San Francisco

The Problem Stated. The requirements to be considered in designing a telephone system for this region may be briefly stated as follows:

1. A system which shall give satisfactory telephone transmission between all points in the whole territory.

2. A system which provides satisfactory accessory conditions such as ease, rapidity and accuracy of completing and controlling connections, methods of charging for service and means for discrimination in the same.

The consideration of these general requirements as applied to the case in hand causes their expansion into ten conditions, *viz.*,

1. Quiet, clear transmission over all talking circuits.

South office, San Francisco

2. Easy, quick and accurate completion of local connections within each exchange district.

3. Provision for the cosmopolitan nature of the population especially regarding the diversity of languages.

4. Measured service.

5. Free service on calls to certain classes of stations.

6. Private branch exchange business.

7 Quick and accurate completion of calls between exchange districts especially between San Francisco and Oakland.

8. Accuracy in charging the accounts of credit toll users.

9. Credit and cash toll work between exchanges.

10. Provision for the harmonious mutual working of different types of apparatus used in the several exchanges.

A Bit of History. In the Spring of 1905 the interest of San Francisco citizens was aroused by a small exhibit of the automatic system. This exhibit was, however, destroyed by the earthquake and fire in the spring of 1906. While the city was recovering from the effects of the disaster the attention of constructionists was diverted to Oakland where an automatic system was installed and completed in May, 1907. It is of the three-wire trunk release common battery type, with Keith type line switches. Three offices are in service, Main East and Berkeley, with two district stations connected to the Main office.

Work was again taken up in San Francisco with the result that a system was installed in 1909. By the time the San Francisco order was placed the two-wire automatic equipment had been perfected and was accordingly used. Four offices are at present operating and are designated as Main, Howard, South and West.

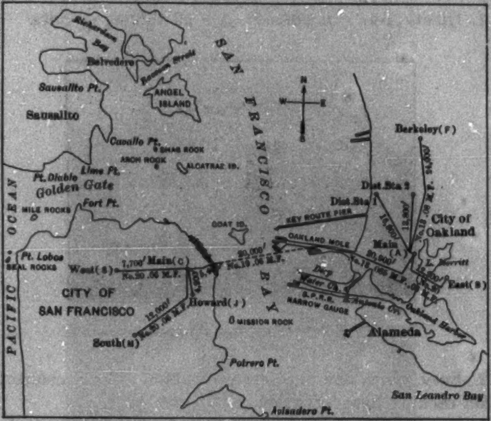
Richardson Bay
Belvedere
Raccoon Strait
Sausalito Pt.
ANGEL ISLAND
Sausalito
SAN FRANCISCO BAY
N
W
E
S
Cavallo Pt.
SHAG ROCK
ARCH ROCK
ALCATRAZ ID.
Lime Pt.
Pt. Diablo
Golden Gate
Fort Pt.
PACIFIC OCEAN
MILE ROCKS
Pt. Lobos
SEAL ROCKS
West (S)
7,700′ Main (C)
No. 20 .06 M.F.
CITY OF SAN FRANCISCO
Howard (J)
12,000′
No. 20 .06 M.F.
South (M)
GOAT ID.
20,000′
No. 19 .06 M.F.
MISSION ROCK
Potrero Pt.
Avisadero Pt.
KEY ROUTE PIER
OAKLAND MOLE
Dist. Sta 1
Dist. Sta 2
Berkeley (F)
City of Oakland
Main (A)
20,900′
L. Merritt
East (B)
Dry
Water Co.
S.P.R.R. NARROW GAUGE
San Antonio Crk.
Oakland Harbor
Alameda
San Leandro Bay

FIG. 1—Map of San Francisco and Oakland

LOCAL EXCHANGE APPARATUS.

Oakland. The locations of the offices in Oakland are shown in Fig. 1. More extended and detailed descriptions of local exchange apparatus have been given from time to time, hence my references will be confined to recalling the types and chief functions of the several switches, in order that the subjects discussed may be more clear.

Each subscriber's line in any office terminates in a line switch (Fig. 2). These line switches are grouped in units (see Figs. 3 and 4) of from 50 to 100 each. All the line switches in a unit have access to a group of ten trunk lines. The general arrangement of switches is shown in Fig. 5. When any subscriber initiates a call, his line is automatically connected to an idle trunk line, *a*. This trunk is preselected, so that there is no loss of time, the connection being practically instantaneous. The various groups of ten trunks each, which come from the banks of the line switch units, terminate in first selector switches.

To the first or bottom level of bank contacts in all first selectors in Oakland are attached trunk lines leading to the Main office. The second level has the trunks leading to the East office and the third level those to the Berkeley office. Taking the East office for example, the trunks from the second level are termed local trunks, *b*, since they run to second selectors in the same office. Those from the first and third levels, however, are outgoing trunks, *c*, for they run to the other offices, Main and Berkeley. These outgoing trunks go through repeaters, which serve the chief purpose of supplying talking current to the calling subscriber from his own office, while still enabling him to send impulses to the distant office to control the switches.

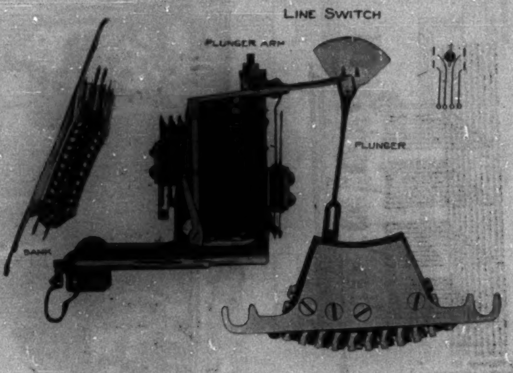

FIG. 2

The second selectors in each office have the duty of picking out the desired thousand group and of selecting an idle third selector in that thousand. The third selector chooses the hundred group and the connector makes the final connection to the line of the called subscriber. In practice the connector switches are mounted on the same frame with the line switches with whose lines they connect. Incoming trunks, *d*, from other offices are wired to second selectors whose banks connect with trunks common to the local apparatus.

The means by which a subscriber controls the switches is briefly reviewed here to make clearer the operation of the special functions to be described later. The two line wires which extend from any Oakland office to a subscriber's station are termed "vertical" and "rotary" respectively. In the office each is connected to a relay which has its other terminal attached to a battery of storage cells. The other (positive) terminal of the battery is grounded. The dial or calling device at the substation, when operated, grounds each wire in a definite way, operating the relays, and through them the switches.

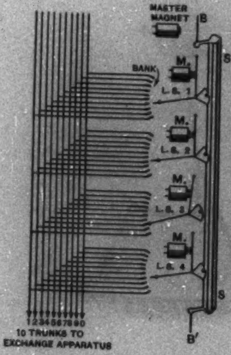

FIG. 3—Grouping of line switches

FIG. 4—Close view of line switch unit

The vertical wire is the impulse transmitting member, for over it are sent at various times the exact number of impulses required to set the switches according to the digit called. The rotary wire is the switching or circuit-changing member. It determines upon what switch or magnet the vertical impulses shall act. At the close of any series of impulses over the vertical wire, one impulse is always sent over the rotary wire to shift the connections in the switches so that the next series over the vertical line will be effective on the next operation to be performed.

When the called subscriber answers, a relay in the connector is operated which switches the rotary wire from negative to positive battery, thus supplying talking current to the calling subscriber.

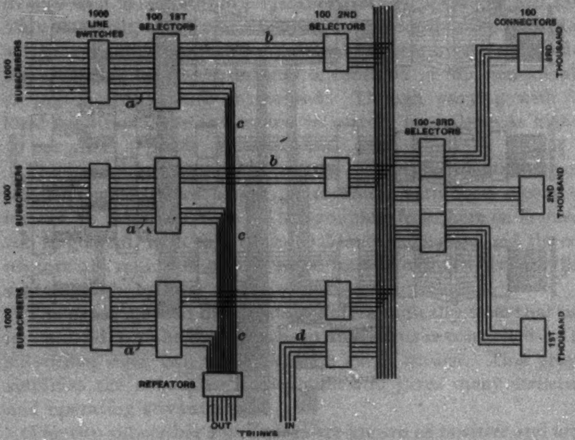
1000 LINE SWITCHES
100 1ST SELECTORS
100 2ND SELECTORS
100 CONNECTORS
3RD THOUSAND
1000 SUBSCRIBERS
a
b
c
100-3RD SELECTORS
1000 SUBSCRIBERS
2ND THOUSAND
a
c
1000 SUBSCRIBERS
a
c
d
1ST THOUSAND
REPEATORS
OUT
TRUNKS
IN

FIG. 5—Trunking in Oakland

The simultaneous grounding and clearing of both vertical and rotary lines causes the switches to be released and restored to normal position.

San Francisco. The relative locations of the four offices are shown in Fig. 1. The grouping of switches is somewhat different from that of Oakland owing to the introduction of secondary line switches. A typical arrangement is shown in Fig. 6.

Each subscriber's line terminates in a primary line switch.

These switches are grouped in units of 50 each, and have access to ten trunks, as described for Oakland. But here the difference begins. The trunks from the primary line switches are carried to secondary line-switch units, where each trunk terminates in a secondary line switch. Each unit group of secondary line switches has access to a group of ten trunks, *d*, each of which ends in a first selector. These secondary line switches are exactly like the primary switches in function, for they pre-select the idle trunks in exactly the same way.

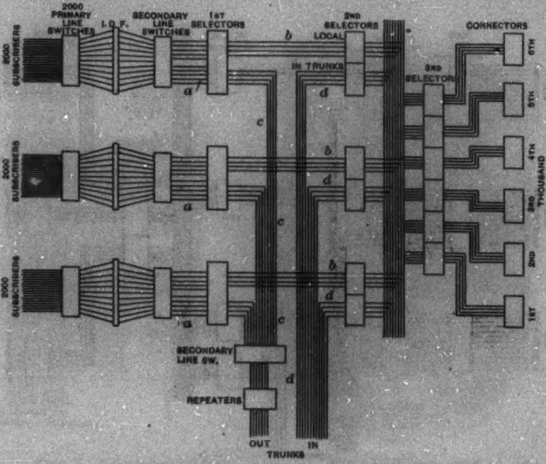
2000 SUBSCRIBERS
2000 PRIMARY LINE SWITCHES
I.D.F.
SECONDARY LINE SWITCHES
1ST SELECTORS
2ND SELECTORS
LOCAL
IN TRUNKS
3RD SELECTORS
CONNECTORS
6TH
5TH
4TH
3RD
2ND
1ST
THOUSAND
a
b
c
d
2000 SUBSCRIBERS
2000 SUBSCRIBERS
SECONDARY LINE SW.
REPEATERS
OUT
IN
TRUNKS

Fig. 6—Trunking in San Francisco

The purpose of using primary and secondary line switches is to enable any subscriber's line to use any first selector switch. This is in the interest of economy. Where only a small number of trunks are available for selection, the efficiency is relatively low. For instance, it has been found in automatic telephone work that ten trunks in one group can be depended upon to handle about 225 busy-hour calls, or 22.5 calls per trunk. Twenty trunks in one group will handle about 575 busy-hour calls or 28.75 calls per trunk. By arranging one hundred first selectors in one group 4,000 busy-hour calls may be successfully handled.

If arranged in groups of ten each it would take about 180 first selectors to carry the same load.

The intermediate distributing frame placed between the primary and secondary line switches is to render more easy the interconnections by means of which the traffic is equalized on all the first selectors.

Since the first selectors select the office in which the called number is located, all levels but one will be connected to trunks to other offices. These outgoing trunks, *c*, are led through secondary line switches so that any inter-office trunk is made available to any first selector. For instance, if we consider a call from Main to South, every trunk leading to the South office from Main will be available for use by every first selector in the latter office. By arranging all the trunks in a common group, considerable saving in trunk cable is secured. Though varying with the local conditions, the saving has in certain cases been as high as 40 per cent.

The incoming trunks, *d*, from other offices terminate in second selectors which have access, in common with local second selectors, to third selectors. The grouping from here on is identical, in general, with that of the Oakland Exchange, and the connectors are mounted on the same frames with the primary line switches, whose lines they are designed to reach.

The exact method of operation differs radically from that used in Oakland, for the San Francisco apparatus is controlled by the subscriber over two wires with no earth return. This greatly sinplifies the subscriber's telephone and gives many structural and operating advantages.

The two subscriber's line wires are known as positive and negative, indicating the terminal of the battery to which each is attached through the windings of the line relay. The series of impulses for stepping up the wipers of the switches is caused by the dial or calling device, which opens and closes a normally closed pair of contacts. The line relay follows these impulses and repeats them to the magnets which move the wiper shaft.

The switching of the circuit to the next switch or operation depends upon the time interval between one series of impulses and the next. During a series, the circuit-changing member is held by a catch, which is released when the impulses cease to come. The release is accomplished by simply opening the line circuit by hanging up the receiver. This momentarily brings into action the release magnets which restore all switches to normal.

1. *Telephone Transmission.* The nature of the completed circuit between two subscribers has a vital effect on the quality and loudness of transmission. Freedom from external disturbances is to be secured by properly transposed wires and perfect electrical balance. The former is secured by a large use of telephone cable, the latter by high insulation and properly designed apparatus. In the telephone switchboards installed in San Francisco and Oakland every talking circuit is balanced from one end to the other. Fig. 7 gives in simplified form the transmission circuit between two subscribers in separate offices. From the calling telephone to the called telephone there are four "bridges" or shunt paths. Each of these is a relay or a pair of relays, all of which are highly inductive, so that little loss is occasioned to telephone current. The impedance of each path from line to earth is made as nearly as possible equal to that of the mate. No extra coils are bridged to one side of the line, and none are inserted in series. All auxiliary circuits are handled by a third wire within each office, leaving the talking circuit clear for its proper functions. The trunks are two-wire with no earth return circuits during conversation. Each subscriber is supplied with talking current from a battery in his own office. No repeating coils are used in any portion of the circuits.

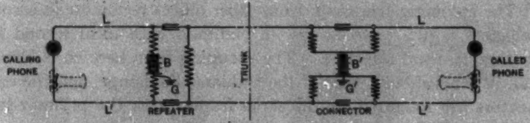

Fig. 7—Simplified talking circuit. Inter-office

2. *Method of Calling.* The method of calling a number on the automatic system has been described by others. Briefly, it consists in rotating a small dial by the finger, making one motion for each digit in the call number. The dial used in San Francisco is shown in Fig. 8. To assist the memory, the offices are designated by letters instead of figures. The code is as follows:

C	Main office.
J	Howard office.
M	South office.
S	West office.

Thus, a telephone whose number is 22785, appears in the directory as J-2785. It is served by the Howard office, though this is of little importance to the subscriber.

The manipulation of the dial for an average call number takes about five seconds, after which the bell of the called station begins to ring without further action on the part of the calling subscriber. The ring is intermittent and ceases when the called subscriber answers.

Instantaneous release of the switches is effected by hanging the receiver on the hook. This is of interest chiefly to those who have two or more calls to make in succession.

3. *Diversity of Languages.* The method of calling above described is of special convenience to the many people who speak only foreign languages. The Arabic numerals are common to practically all nationalities represented in San Francisco except the Chinese. For the latter a special lettering has been made which is shown in Fig 9.

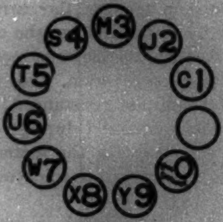

FIG. 8—San Francisco dial

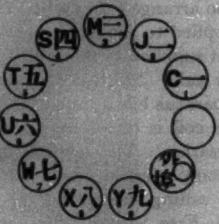

FIG. 9—Chinese dial

4. *Measured Service.* One of the conditions met in managing a telephone system in a large city is the desirability of charging for the service in proportion to the amount of service rendered. This is ordinarily done by attaching a meter to each subscriber's line. The requirements of a meter are as follows:

1. It must register only once for each completed connection, rejecting those in which the called station fails to answer.

2. It must make no charge for connection to certain classes of telephones, such as fire, police, information and complaint desks, etc.

The Oakland exchange is operated on the flat rate basis for all calls originating and terminating within the exchange, which includes the suburb of Berkeley. In San Francisco measured service is required.

The meter in an automatic telephone system is attached to the line switch. As above mentioned, it must not operate until the called station answers. Therefore, the latter act must cause some change in electrical condition at the line switch which will cause the meter to register. The line switch of the calling station and the connector which picks up the called line may be in different offices with 1st, 2nd, and 3rd selectors and a repeater in the circuit between. The called station can control the connector and through it the condition of the line leading back to the line switch. Two changes in condition are available, reversal of current and change of current strength. The latter is undesirable on account of its interfering with conversation to stations set aside for free service. The former seemingly necessitates some form of polarized magnet. As it was desired to avoid the use of permanent magnets, a two-coil meter was devised. It is so arranged that when the called station answers, the current supplied to the latter operates the relay which reverses the current supplied to the calling line. This causes the meter to record one call. Neither coil alone will cause registration, and the apparatus has a range from 0 to 1,500 ohms line resistance. Its line coil is of low resistance and is short-circuited during conversation. The reversal of current for operating the meter is accomplished in such a manner as not to cause inconveniences to the calling subscriber.

5. *Free Service*. Since the connector is the switch in which occurs the reversal of current which operates the meter, the means for giving free service must effect this part of the apparatus. It is done by grouping all free service lines such as information, police, etc , into one or more hundred groups, each group served by a set of connectors. All these connectors are so wired that the current flow to the calling subscriber is not reversed when the called station answers, consequently no register is made.

There is one class of calls for which, strictly speaking, no charge should be made, and that is calls which result in the wrong number being obtained. The meter makes no discrimination here, and if the called station answers, a call will be recorded. However, experience has shown that such a small per cent of wrong numbers are obtained that they may safely be neglected. This is especially true if wrong calls due to carelessness in the use of the dial be omitted. For these it is right to expect the subscriber to pay. The same is true of regular manual practice, for if a subscriber calls for the wrong number and gets it, he is expected to pay for it.

Fig. 10 is a general view of a number of primary line switches. In the space above the switches indicated by the letter *M* the meters may be seen. These are in tight cases which are locked and accessible only to the official who has charge of meter reading.

Cash measured service is furnished by means of coin boxes attached to the line wires at the subscriber's stations. No coin is required to be deposited in order to call. When the called station answers, the reversal of current operates a magnet in the coin box which short circuits the transmitter and places a shunt in parallel with the receiver. This prevents the transmission of speech, but allows the user to hear faintly the voice of the called subscriber. By dropping a coin in the chute, the shunts are removed, so that conversation can take place.

FIG. 10—Primary line switches with meters

When a call is made to a free station as above described, no reversal of current takes place, so that the calling subscriber is not forced to make a payment.

6. *Private Branch Exchanges.* In both Oakland and San Francisco the nature of the business makes quite a large number

of private branch exchanges profitable to the subscriber and to the operating company. These boards are manually operated and have several trunks connecting them with the nearest public exchange office. Each business house is listed under one number in the directory. When a public subscriber selects the call number the connector switch must automatically select an idle trunk to the private branch board. This is done by a special type of switch known as the rotary connector. It responds to the impulses for the tens and units digits of the call number, but immediately thereafter acts as a selector until an idle trunk is found. These rotary connectors are grouped in hundreds so that in providing for this special service the call numbers are set aside in blocks of one hundred each. Thus in the Main office San Francisco, the 1100, 1200, 2100, 2200, 3100, 3200, 4100, and 4200 hundred units are set aside for private branch exchange service and no number in them assigned for individual lines.

Let us suppose that the call number of a certain wholesale house is C-4251 and that four trunks are required for the business. The connector switches in the 4200 group of the Main or C office will serve this board. These four trunks will be multipled to the first four sets of contacts in the fifth level of the connector banks, that is, corresponding to numbers 4251, 4252, 4253, and 4254. Contacts 4255 are connected to the busy tone so that if it happens that all trunks are occupied, the calling subscriber will receive the busy signal and be induced to release. The private contacts 4255 of the several connector switches are not multipled together. If while all four trunks are occupied, more than one called is received for the busy number, the second and later calls will also stop on 4255 and not be forced past to 4256 which might be assigned to other service.

If desired, the remaining four numbers in this same level, 4256, 4257, 4258, 4259 may be given to some other private branch board. In fact any grouping of the trunks of a level may be used, it being only necessary to reserve one set of contacts at the end of each group for busy indication.

The trunks to private branch board are treated exactly like subscriber's lines in the public exchange, each being wired to a line switch for calls to the automatic system. They terminate in jacks and signals on the manual private boards and can be used for establishing connections either to or from the subscriber. The operator is provided with a calling device which may be switched by keys to any cord circuit. With this the operator calls into the automatic exchange and arrangements are made so that complete double supervision is secured on all calls.

In the case of a private branch exchange having sufficient magnitude of business to require it, the trunks leading from connector banks may be made one-way only and reserved for calls to the branch board. There will then be installed as many trunks from the latter to the public exchange as are necessary, these trunks being attached to line switches. The number of trunks is not limited by the number of contacts in a level of the connector bank.

7. *Transbay and Suburban Toll*. We come now to what is perhaps the most interesting feature of the combined telephone exchanges. On account of the relative positions of the two cities, and their close business and social relations, the matter of quick and satisfactory communication between them is of great importance.

The fact that a charge is made for all calls between the two cities makes it necessary to employ operators for putting up these connections, making records of the same.

Long distance toll work is necessarily handled in a different manner from suburban calls. In the former, the telephone company agrees to bring together two persons, in the latter merely two telephones. This is sometimes called the "two number basis" inasmuch as only the two numbers are recorded, no attention being paid to names.

A common method of handling suburban as well as long distance calls is to have each call received by a recording operator, who makes out a ticket. She tells the subscriber that he will be called when the line is ready. The ticket is then passed to a line operator, who calls the distant city and with the coöperation of a similar operator there, establishes the desired circuit. She then calls the station whose number was given by the person originating the call and allows the conversation to take place.

For the suburban work between San Francisco and Oakland it was thought best to abolish this slow procedure and use what is known as the "rapid fire" method. Accordingly provisions were made for allowing the recording operator at San Francisco, for example, to complete the call into the Oakland exchange by a calling device in San Francisco, and to allow the conversation to proceed at once. This virtually makes the recording operator a line operator and entirely dispenses with the services of a line operator to complete the connection in the distant office.

The recording operator is of course obliged to ask the subscriber who originates the call for his telephone number so that the cost of the toll service may be properly charged. It is to be expected that, either by accident or intention, wrong numbers will sometimes be given. To prevent error from this source a system of back checking has been devised, which will be described in detail later.

The operators are divided into two main groups, suburban and long distance. The latter are as usual made up of recording operators and line operators, each with the usual duties assigned.

The suburban operators work in pairs or threes and are termed suburban operators and checking operators. All calls for out of town come to the suburban operators, who act as distributors between the two boards. This is because of the relatively heavy nature of transbay and suburban service as compared to long distance service. The suburban operator puts up suburban connections while the checking operator verifies the correctness of the number given by the calling subscriber. Usually one checking operator verifies the work for two suburban operators, though during periods of light load the latter check for themselves.

The method adopted in making a call is as follows: The subscriber takes his receiver from the hook and calls the digit "0" on the dial. This lifts the wipers of a first selector to the top level and selects an idle trunk to the suburban board. Here a lamp attracts the attention of a suburban operator who answers the call by plugging into the jack and throwing the listening key on her cord circuit. She asks whether "suburban" or "long distance" is wanted. If the latter, she momentarily depresses the transfer key button associated with the trunk in use. This automatically transfers the call to the long distance recording board, where multiples of the incoming trunks appear. The proper operator, seeing the burning lamp, answers and cares for the call in the usual way.

If, however, the subscriber replies that he wants "Suburban", the suburban operator asks him two questions.

"What number do you wish?"

"What is your number?"

This information she writes on a ticket together with the number of the incoming trunk over which the order was received. The pad of tickets bears the suburban operator's position number and is arranged to furnish duplicate copies. Having recorded the information she passes the duplicate ticket to the checking operator who is seated directly in front of her. The two following operations are then performed simultaneously:

The suburban operator selects an idle outgoing trunk leading across the bay and calls the number in the distant exchange by means of her dial. The checking operator upon receiving the ticket plugs into the multiple of the incoming trunk shown thereon. Then by an independent set of apparatus she calls the number of the originating subscriber. If the checking operator finds that the number written on the duplicate ticket is wrong, she passes the ticket back to the suburban operator by dropping it in a special ticket box in plain view. The latter operator at once throws the cut-off key on the cord, thereby severing the connection from the outgoing transbay trunk. She then requests the calling subscriber to repeat his number. If he repeats the number previously given, she informs him that she can not reach him over that number. In most cases the subscriber now corrects his mistake by giving the true number. This is now entered on the tickets and the duplicate again passed to the checking operator for verification. Usually the suburban operator allows the connection to proceed, while the second check is being made, for, as a rule, the second number is found to be correct.

On the suburban operators cord circuit is provided two supervisory lamps which have the usual functions. The calling supervisory lamp burns till the subscriber in the distant office answers. Then the operator stamps the ticket in a calculagraph. At the end of the conversation both subscribers hang up the receivers. This lights both supervisory lamps. The operator then times the ticket and disconnects the circuits.

The completed circuit over which conversation is carried on is shown in simplified form in Fig. 11. It is balanced and quiet in service. The rapid break and make of the calling device in operating the switches through the cable under the bay causes no inconvenience to those using parallel trunks.

When a subscriber has secured connection with the suburban or toll board, it is necessary that he be permitted to signal the operator by moving his receiver hook up and down. This would ordinarily cause the release of his first selector since all automatic switches are arranged to be released by the depressing of the hook lever. To prevent this breaking of the connection a special arrangement is attached to the outgoing toll trunks from each office in place of the regular repeater. This enables the release of the first selector used by the subscriber to be controlled by the operator.

After the subscriber has hung up, the operator pulls out her plug which automatically causes the release of the first selector.

8. *Toll Checking Apparatus.* In the preceding general description of the mode of operation, reference was made to the toll-checking operator and her apparatus. The general plan of checking is to connect to the incoming toll trunk in use a source of alternating current which produces a musical tone. By independent automatic switches the checking operator calls the number given. If correct she will obtain connection to the same line as that over which the call was received by the suburban operator, and by listening can hear the tone. The condition is shown in Fig. 12. The subscriber at the right has called the suburban operator over the incoming toll trunk. The operator has answered and made out the ticket. The checking operator has used a checking trunk to secure connection with the number given. At this point she presses the check tone key which connects to the incoming toll trunk a source of alternating current which produces a sound differing from the regular busy tone of the exchange. If the number is correct, the tone will be carried back over the toll trunk to the connector multiple and thence over the checking trunk to the checking operator.

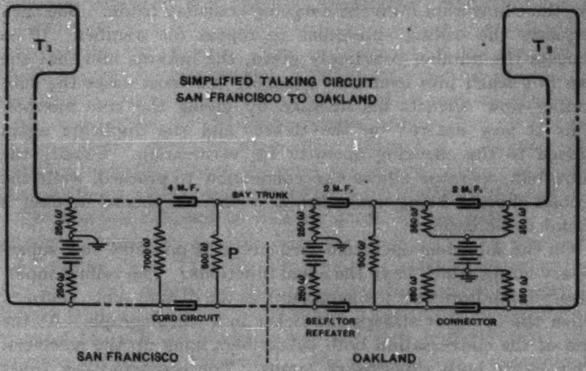
T₁
T₂
SIMPLIFIED TALKING CIRCUIT
SAN FRANCISCO TO OAKLAND
4 M.F.
BAY TRUNK
2 M.F.
2 M.F.
250 ω
250 ω
7000 ω
500 ω
P
250 ω
250 ω
500 ω
350 ω
350 ω
350 ω
350 ω
CORD CIRCUIT
SELECTOR REPEATER
CONNECTOR
SAN FRANCISCO
OAKLAND

FIG. 11—Simplified transbay talking circuit

The ordinary connector cannot be used by the checking operator in picking up the calling subscriber's line, because the latter is protected by a busy test which will not permit an ordinary connector to establish connection. For this work one check connector is provided in each hundred group. It is devoted exclusively to testing and checking. It is provided with three pairs of wires, one pair (*A* and *B*) for carrying the tone, another pair (+ and –) for operating the magnets for lifting and rotating the wipers and a third pair for auxiliary purposes.

The checking operator secures connection with the check connector in any hundred in any office by a system of first, second and third selectors which is entirely separate from the regular apparatus of the exchange. One first selector repeater is provided for each checking operator, to enable her to select a trunk to any office in the exchange. In each office as many second selectors and third selectors are provided as are necessary for the work, the number varying in the different offices. These are operated by a calling device located at the checking operator's position.

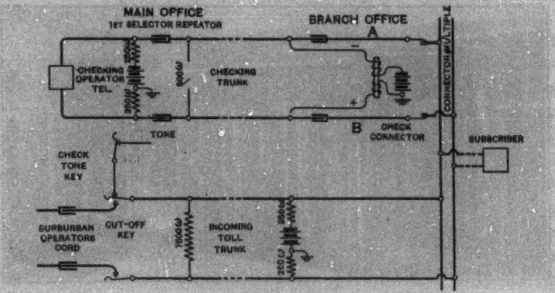
MAIN OFFICE
1ST SELECTOR REPEATER
BRANCH OFFICE
A
–
+
B
CHECKING OPERATOR TEL.
250ω
250ω
500ω
CHECKING TRUNK
CONNECTOR MULTIPLE
TONE
CHECK CONNECTOR
SUBSCRIBER
CHECK TONE KEY
SURBURBAN OPERATORS CORD
CUT-OFF KEY
7000ω
INCOMING TOLL TRUNK

FIG. 12—Simplified toll checking circuit

When the checking operator plugs into a connection it lights a red lamp associated with the suburban operator's cord circuit. This shows that the checking operator has picked up the trunk. When the checking operator has verified the number and withdrawn her plug the red lamp is extinguished, thus notifying the suburban operator that the number has been checked and is correct.

As a guard, tending to prevent the checking of wrong trunks, the checking operator's cord circuit is provided with a lamp. This lamp will light when plugged in on a trunk which is waiting for the completion of a connection. If, however, the checking operator by mistake plugs in on a non-busy trunk, or one over which a connection has been completely established the lamp will not burn.

9. *Credit and Cash Tolls.* The larger proportion of the calls between the two cities are handled on the credit basis. From the records of the toll tickets, statements are made out at regular intervals and sent to the subscribers for payment. For such public places at which it is desirable to collect cash for suburban and long distance service, a regular coin box is attached to the telephone. The dropping of the coin gives a signal which reveals its denomination to the operator.

FIG. 13—Secondary line switches

10. *Two Three-wire Operation.* In the general description of suburban toll operation a short reference was made to the trunk lines connecting the two cities. For the purpose of giving a better idea of the arrangement, a trunk line will be described which handles calls from San Francisco to Oakland.

The work of interconnecting the two exchanges was rendered more difficult by the fact that the Oakland apparatus is three-wire, while that of San Francisco is two-wire. The two-wire system requires only the opening and closing of the line circuit. The three-wire system requires each line wire to be grounded in a certain order. The San Francisco recording operator using a two-wire calling device was required to operate three-wire selectors and connectors in Oakland, in some cases as far as thirteen miles away. This was done by means of repeaters which handle the impulses somewhat like a telegraph-repeater, except that it is necessary to transmit impulses only one way.

Each transbay trunk from San Francisco to Oakland ends in multiple jacks with visual busy signals on the San Francisco suburban board, and in a first selector-repeater in the Main office in Oakland. This switch is a first selector, to pick out trunks to the desired office in Oakland, combined with a repeater arrangement to convert the simple make and break of the two-wire system into the alternate grounding of vertical and rotary lines required by the three-wire system. The release of the connection as well as proper supervision is also provided in the repeater.

The operator is provided with a set of plugs and cords with which to connect incoming trunks from San Francisco subscribers to outgoing trunks to Oakland. A calling device is mounted on the keyboard and arranged to be switched into any cord circuit by keys. When a call comes in over an incoming trunk, it is answered by inserting the answering plug of a cord into the proper jack. An idle outgoing trunk to Oakland is selected by inspection of the visual busy signals, and the calling plug of the cord in use inserted into the jack. The calling device is then switched into the cord circuit and rotated in accordance with the desired number. This operates the switches in Oakland.

The supervision is accomplished as follows: Across each cord circuit of the suburban operator in San Francisco is bridged a polarized relay, *P*, Fig. 11. Normally the current from the first selector repeater in Oakland is in such a direction as to cause the relay to light its associated lamp. In the Oakland exchange the circuits from the first selector through to the connector are three-wire. When the called subscriber answers, it causes the rotary line to be switched from negative battery to ground or positive battery. This energizes a pair of relays in the first selector repeater which reverses the current supplied by the latter to the operator's cord circuit in San Francisco. This reversal causes the bridged polarized relay *P* to operate, extinguishing the supervisory lamp.

The release of the three-wire Oakland apparatus calls for the momentary simultaneous grounding of the vertical and rotary lines. The two-wire first selector repeater at the Oakland end of the transbay trunk requires only the simple opening of its line circuit By a suitable arrangement this is made to cause the release of the three-wire apparatus according to the manner just indicated.

The trunks from Oakland to San Francisco are operated straight two-wire, and hence are simpler than those just described. For the sake of securing sharper, better signals the trunks are wired through the first selector repeaters in the San Francisco main office. Supervision is secured by marginal relays.

DISCUSSION ON "THE AUTOMATIC TELEPHONE IN RELATION TO CITY SERVICE." JEFFERSON, N. H., JUNE 29, 1910.

Frank F. Fowle: Mr. Smith's paper is a very interesting description of the general features of a large automatic installation, from an operating standpoint. The descriptive nature of the paper does not permit of elaborate discussion, but there are several novel features worth emphasizing.

The ingenious method of checking suburban toll calls, with the "rapid fire" or "express" method of operating, is especially interesting. It does away with the drag on the service caused by releasing the calling subscriber and then calling him back when the connection is ready—a procedure which, as Mr. Smith describes, is only necessary to verify his number and prevent mistakes or fraud.

The problem of a meter for measured service seems to have been solved to the same degree that it has been worked out in manual practice, but it is yet lacking from the standpoint of the subscriber. The only satisfactory solution to the subscriber will be an indicating meter at his telephone, which he can read himself. The means for accomplishing this appear to be at hand, both in manual and in automatic service. There seems to be some apathy towards realizing this ideal arrangement on the part of telephone companies, due no doubt in part to the cost of an extensive change in subscribers' equipment, and in part to a belief that the public does not demand it. On the latter score, the public has been discouraged in some cases into believing that this ideal plan is very costly and difficult of achievment.

Coin boxes for prepayment service have long been in use in manual systems. They have been operated under two plans, one requiring the deposit of the coin to signal the operator, and the other requiring the coin to be deposited after the order has been given, when told to do so by the operator. The former plan is used in business districts, the latter in residence districts, where it might occasion some inconvenience to find a coin in an emergency or late at night. Under both plans, the operator controls the disposition of the coin by means of keys in her cord circuit, sending it into the coin box if the call is completed, or returning it to the subscriber if the call is not completed.

Mr. Smith describes a device by means of which the coin box is employed in automatic prepayment measured service. The coin here is not deposited until the called party responds, and then it must be dropped in the box in order to take a short circuit off the transmitter at the calling station.

This form of service admittedly has disadvantages in public places, stores, waiting rooms, etc., but on the other hand it has admittedly several disadvantages for offices and residences. In view of the fact that this class of service is usually charged for at a low minimum, it comprises in some cities a large part of the whole development, and considerations affecting it are therefore important.

The functions now controlled at the subscriber's station could be arranged to operate a meter dial and thus register the call within sight of the calling party, thereby doing away with the objections to the coin box in office and residence service. The costs of reading and collecting might be slightly greater than they are with the present system, but not such as to increase the total cost of operation to any appreciable extent. It is quite conceivable that the meters could be read by calling the subscriber on his telephone and asking him for the reading, although in such a case it would be necessary to have duplicate meters in the exchange, as a check.

A meter situated in the exchange, assuming that to be the only meter, is beyond the control or observation of the subscriber, and theoretically this is not the proper place for it, although such an arrangement is both convenient and economical for the company. There is natural suspicion of such a plan on the part of subscribers, particularly when they are unable to check their bills.

Under the proposed plan, the meter should not cost more than the present coin boxes, and probably less. The maintenance costs should also be no greater.

The writer asks Mr. Smith the following questions in regard to automatic practice in San Francisco and Oakland.

1. In the case of manual private branch exchanges, what arrangements are made for night service when no operator is on duty? That is, is there any practice which corresponds to the plan of connecting certain extensions through the branch board to the exchange for night service, as in full manual systems?

2. In the case of manual private branch exchanges, are the extensions equipped for automatic or manual operation, or both?

3. Are automatic, unattended private branch exchanges in demand or in use?

4. Has party line service been developed, and if so, of what classes. Is selective ringing employed?

5. What standard of transmission in terms of No. 19 B. & S. gauge cable with 0.054 or 0.060 mf. per mile, was employed in laying out the distribution, and the toll trunks, for all service in the automatic zone?

Geo. D. Shepardson (by letter): The telephone exchange systems present an interesting case of the gradual displacement of sentient actions by automatic operations which has been going on in most lines of industry. It is common to distinguish between "manual" and "automatic" exchanges according to whether human effort at the exchange is or is not required for performing the various operations of connecting the calling and the called subscribers. As a matter of fact, manually operated systems use more and more automatically operated devices, and automatic systems require more and more manual operation as they become more and more extensive. The exact stage where a given system shall change from automatic to manual operation or vice versa is a question partly of simplicity of design and of certainty of operation, and partly a question of required investment and of dividend-earning capacity.

The first impulse or judgment regarding automatic telephone systems is that they may be suitable for small towns, but that they are inherently outclassed by manual systems when applied to the multifarious demands of large business communities. It is interesting to learn that practically every service has been met successfully by automatic devices, with the single exception of toll service, where partially manual operation is found desirable. Theoretically the automatic system could take care even of such service, and the probable reason for the introduction of manual operators at this stage is doubtless due to financial rather than to purely theoretical or engineering considerations.

The various checks on measured and toll service are of much interest. The feeling that an automatic apparatus is insentient probably adds greatly to the instinctive desire of customers with weak or perverted moral natures to "beat the company." A somewhat similar tone-test on the line of the subscriber reported as calling for a toll connection might save full-manual systems some trouble from tolls erroneously or viciously charged against an innocent subscriber.

The development of the automatic telephone system has proceeded to a stage that compels admiration. Both the electrical and the mechanical features bear evidence of careful forethought and of fruitful experience. A detail that contributed much to the successful operation of switching devices at a considerable distance from the battery, is the minimizing of friction in the selecting switch by having the plunger move to the chosen position before coming into contact with the fingers or jacks.

An equally ingenious feature of the earlier exchanges was the use of one side of the line for selecting the bank or group, while the individual unit was selected over the other wire. In the later development the successful use of the time element in differentiating between the group and the individual, bears evidence of careful design and development. The elimination of the ground connection doubtless removes a source of considerable stray noise and other trouble. But a question arises as to whether trouble is not experienced in requiring the calling subscriber to observe a certain rapidity in making successive settings of the dial, lest too long an interval result in automatically cutting off the connection before it is complete.

The use of primary and secondary line switches for saving time and trunks seems closely analogous to the development of local automatic exchanges for handling business of a district at some distance from the main exchange, such as are being used as auxiliaries to automatic or manual exchanges.

The mention of difficulties arising from the Chinese method of counting, prompts the suggestion that French girls should make good telephone operators on manual boards having twenty jacks in each row. For, if the French think as they speak, they think in twenties rather than in tens. Thus, instead of thinking of 88 as eight tens plus eight, they apparently think of it as four twenties plus eight, for they call it "quatre-vingts huit." The neophyte French operator would automatically look to or reach for the fifth row of jacks instead of for the ninth row as would be more natural for the ordinary girl.

A point of especial interest in the automatic system as presented in this paper is the simplicity of the talking circuit and its freedom from series impedances and objectionable leakages.

Altogether, the system here presented seems to be a triumph of inventive skill, of engineering research and of financial perseverance and courage.

L. M. Antoine (by letter): The paper is limited to a description of the San Francisco plant and does not touch on the advantages to be derived by the system installed there over other systems originally installed.

A point which appealed to me was the small number of switches used, and the flexible arrangements by which these few switches were made to handle the load. The elimination of all superfluous equipment should carry with it many advantages, such as lower first cost, less floor space, reduced maintenance cost and more efficient service due to less chances for trouble. The latter two points are of paramount importance to an operating company, for a lesser amount of equipment will require fewer switchmen to attend it and can be more carefully watched. At the present time first class switchmen are very hard to get and command good salaries. Practice has shown that equipment in constant use is less subject to trouble than that which is only used occasionally, for dust will collect on contacts and moving parts of idle switches, and make their operation sluggish and uncertain.

Another problem which has confronted operating companies, and which seems to be satisfactorily solved in this system is that of giving good measured service. It is not an easy matter to design a meter that will automatically register completed pay calls only and eliminate incomplete and busy calls, calls to free numbers, etc. It has evidently been accomplished and the device and circuits are so simple that its operation should be positive.

One of the strong points of this system is its efficient private branch exchange service. In Portland, Oregon, nearly 25 per cent of the automatic telephones are stations on private systems of some kind. In the standard private branch exchange the trunks and stations terminate in jacks with lamp signals at a small manual switchboard and each station is equipped with an automatic telephone.

Taking down the receiver signals the operator who connects the calling station with a trunk, or another local station asked for. All local calls are completed manually by the operator, but on trunk calls the station does the calling and releasing automatically. This is a great advantage for when the station has been connected to a trunk the calling party can operate as on a main line telephone, and call as many numbers as he desires without attracting the attention of the operator. Until he hangs up his receiver for a period of time longer than that required to release the call the operator gets no supervision. On incoming calls from the central office the rotary connectors select the idle trunks, as described in the paper under discussion. All are two-way trunks. The board is equipped with a calling device enabling the operator to do the calling if desired.

Automatic intercommunicating service has been perfected to such an extent that it is very desirable in private systems of but a few stations. The operation is the same as that of a manual intercommunicating system, except that the calling is done automatically.

Another kind of service that is growing into favor is that of inter-communicating between extension telephones on a main line. A party on one extension wishing to talk with another on the same line calls an eight on his dial which connects his line to a specially designed switch. This switch sends out generator to ring bells on his own line, and also furnishes talking battery. By using different rings for each extension it makes a very satisfactory office system.

A service which is being extensively used is that of a house system in connection with main lines in apartment houses. The main lines are wired in the regular way except that they are multipled into sets at the vestibules, tradesmen's entrance and janitors' quarters. These sets are equipped with push buttons —one for each apartment—with the name of the occupant opposite. When calling any apartment over one of these sets it is merely necessary to press its respective button to ring. On removing the pressure the push button restores itself part way and remains in a talking position until the receiver is hung up, when the button is restored to normal. All 'phones in apartments are so wired that if a push button is depressed before the dial is rotated the bell at the janitor's station is rung and a drop corresponding to the calling telephone energized. If a subscriber wishes to make a trunk call he makes it in the regular way. As soon as the dial is rotated the janitor signal circuit is open.

Toll service is one of the most essential requisites for the success of any telephone system, for the value of a telephone to the subscriber depends as much on the number of subscribers he can reach as on the quality of the service. When toll traffic is as heavy as it is between San Francisco and Oakland, too much attention cannot be given to the development of an efficient and rapid system. With the system installed at San Francisco and Oakland the service should be very rapid, for the suburban operator dials the required number and the checking is done later.

A. B. Smith: Answering Mr. Fowle's questions in order, I will state as follows:

1. Private branch exchanges, which are used in connection with automatic public exchanges, are given the same night service as is customary in an all manual plant. Such telephones as it is desired to connect up for the night are equipped with automatic calling devices. They are thus enabled, when plugged up to trunk lines for the night, to operate the automatic switches in the public exchange just as if each were on an ordinary subscribers line.

2. As indicated above, only such telephones in the private branch exchange are equipped with calling devices, as are expected to be used for direct calling. Owing to the simple nature of the calling device, it is an easy matter to equip any manual telephone in the branch exchange so that it will be able to operate the automatic switches.

3. Unattended, automatic private branch exchanges are in demand and are in use in a number of places.

4. For many years party line service has been given by automatic exchanges. The four frequency harmonic system is employed, using 16-, 33-, 50- and 66-cycle currents to ring the bells. Both two-party and four-party service are in use.

5. Since the matter of transmission standards falls within the field of the constructing engineer, I will leave the discussion of this point to Mr. S. G. McMeen.

Professor Shepardson's remark regarding the time element necessary in two-wire automatic operations, requires a little explanation. When the subscriber takes his receiver from the hook, a circuit is closed through the telephone in exactly the same way as in any ordinary common battery telephone. When the dial is rotated to send in the impulses for any given digit, it merely opens and closes the circuit as many times as there are units in the digit; that is, if the subscriber pulls the dial for the figure 3 the calling device would open and close the circuit three times, and would come to rest with the circuit closed.

If the subscriber so desires, he may wait several minutes between successive settings of the dial without causing any further inconvenience than to delay the completion of his call. The release is initiated by the opening of the line circuit which is done by the hanging of the receiver on the hook.

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INTERACTION OF FLYWHEELS AND MOTORS WHEN DRIVING ROLL TRAINS BY INDUCTION MOTORS

BY F. G. GASCHE, M. E.

Recent innovations in the method of driving roll trains by the induction motor as accompanied by a rotor of considerable inertia effect has compelled the study of a dynamical problem of some complexity. The problem is essentially a commercial one in requiring that the mechanism involved shall exhibit the greatest return on the investment. This unavoidably imposes the consideration of the prime mover as well as the motor and equipment immediately attached to the roll train. While a complete statement of the solution of this commercial problem cannot be evolved at this time, it is the purpose of the following analysis to exhibit the manner of disposition of certain important elements.

The examination of the phenomena of motor and flywheel action by analytical processes is proposed in view of the practical impossibility of establishing the important items by the use of recording wattmeters, tachometers, or other instruments. The time intervals are so short that the inertia and other instrument defects introduce large errors even with perfectly constant voltage. Constancy of voltage with any power plant connected with a rolling mill is yet to be observed, so that direct experimental examination of the actions considered herewith is not an inviting prospect.

Roll train resistances, particularly on the heavier types of mills, are so exceedingly variable that no type of prime mover, gas engine, steam engine, or steam turbine, can withstand the sudden applications of load without the risk of troublesome, if not dangerous, speed variation unless one or more flywheels exist in the system of motor drives. In addition to this there is imposed a high cost of conversion and the extra expense due to peak loads in the absence of flywheels.

More than this, if several large systems of roll trains are operated from a central electric power plant, it will be found, sooner or later, that it is structurally and commercially inexpedient to provide a suitable flywheel effect on the prime movers to meet the load variations on the entire system of power transmission. The shocks on the motor shaft driving a roll train are such that safe dimensions are almost forbiddingly large. Without the presence of a flywheel on the motor shaft, this shock, and the accompanying momentary demand for energy, is instantly transferred to the shaft and flywheel of the prime mover.

The motives for the application of a flywheel to a motor-driven roll train can be thus indicated:

a. Providing reservoirs of energy exterior to the power plant, in excess of the structural and commercial possibilities of flywheels on the prime movers, or of storage batteries.

b. Equipment of the roll trains with an independent means of freeing the rolls of the bars, in case the motor becomes suddenly inoperative.

c. Raising the load factor on the power plant.

d. Reduction of size and costs of installation of motors, particularly with variable roll train loads.

With reference to the first item, it may be said that the flywheel performs functions in the way of instantaneous and precisely measured delivery of energy with an efficiency of practically 98 per cent, and with a cost of installation that would make a storage battery the alternative to be avoided.

The second item is a consideration of the first importance to any practical mill man. The repetition of roll changes, involving loss of operative time, and the removal of "cobbles" or defective bars, could easily impose a financial loss that would lead to the condemnation of a given motor drive.

Item *c* is almost beyond discussion, as the approximation of uniformity of demand on the prime mover is an advantage that can be appreciated by all.

Concerning item *d*, it may be urged that the mill operation, known as a roll "pass", is accompanied by characteristics in the nature of expenditure of energy that are not to be found on any other system of electric power transmission. The nature of these resistances will be explained in what follows, but attention is directed to the consideration of an element of first importance, *viz., the time required for the "pass", as well as the time between "passes", is established by operative mill conditions.* These time intervals are generally so short that the frequency of automatic change of controlling devices may be considered as very objectionable, if not physically impossible. The deduction from this requirement is that the "secondary resistance" of a motor cannot in general be changed to make available two forms of "slip curves" during the time required by a pass. The "torque-slip" relations having prevailed up to the instant the bar enters the rolls, these relations must continue in most cases until the "pass" has been completed. Since a certain amount of "slip" is necessary in order to realize a torque incident to the resistance of a roll train, it remains to determine how this "slip" shall be distributed over the time required for the "pass", or a portion thereof. On first sight it would seem possible to employ the minimum of slip and use a motor exerting a torque equal to the roll train resistance when working at its most economical load. An alternative would be to use a motor of lower rated capacity, operating on a greater amount of "slip" in coming to full torque, and supplement the tardy response of the motor by the action of a suitable flywheel. If this alternative does no violence to the efficiency of power transmission, it at least favors a lower cost of installation. On certain types of small mills the first method of driving may serve a purpose with a slightly higher electrical efficiency, without the palpable exhibit of a flywheel, but the inertia effect of the rotor itself will generally in such cases be a considerable item to the advantage of the construction.

It will be shown in what follows that, *on the assumption* of perfectly rigid roll train connections and a rotor without any inertia effect (if such were possible), the induction motor is physically incapable of assuming any roll train load above the friction load that by some means may have been imposed on the motor. On the larger sizes of roll trains the shock imposed on the rolls and connections, due to the action of a powerful motor of small slip, will prove such a destructive agent that the experience will be at least a costly one. The nature of shock arising at the motor shaft can be understood from the following study of the characteristics of a roll pass. (See Fig. 1.) As the bar strikes the rolls at *a* preparatory to entering the groove, there is an increasing resistance to the driving mechanism until the forward extremity reaches *b*, the smallest section of the groove. The resistance at this point *b* becomes a tangential effort at the roll surface remaining constant until the rear end of the bar reaches the point *a* at the rolls, when it diminishes to zero as the rear end of the bar reaches the point *b*. In addition to this resistance there is a constant resistance, due to the light running of the roll train, which must be added to the above in referring the energy requirements to the motor shaft.

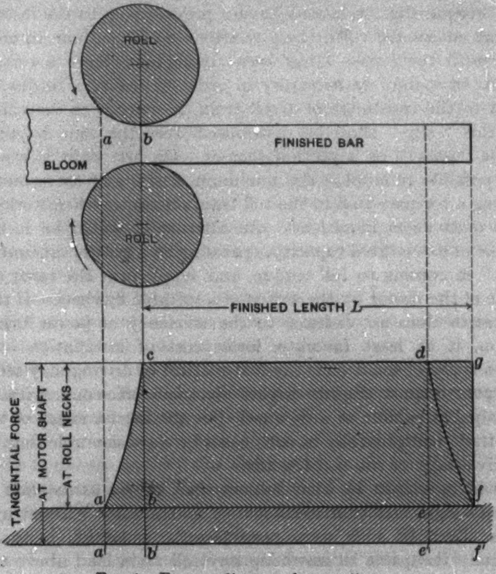
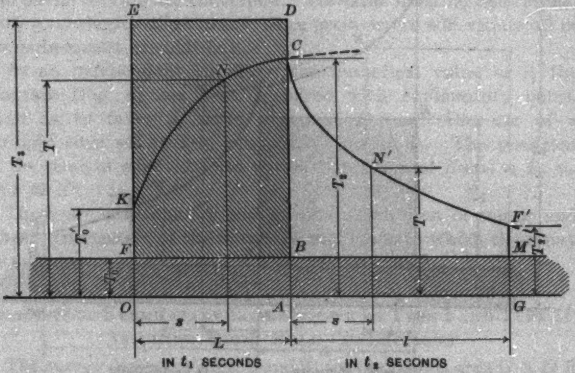

ROLL
a
b
FINISHED BAR
BLOOM
ROLL
FINISHED LENGTH L
c
d
g
TANGENTIAL FORCE
AT MOTOR SHAFT
AT ROLL NECKS
a
b
e
f
a'
b'
e'
f'

FIG. 1—Energy diagram for a roll pass

The operation of a roll pass may be represented by a diagram of energy *a' a c d f f'*. The "approach load" *a' a c b'* is due to causes above explained, as is also the "terminal load" *e' d f f'*.

In some of the larger mills the portions *a b* and *e f* may be a large percentage of the total distance *a f* for the pass. In many problems of design it is sufficient to consider the diagram of neergy for a pass as the rectangle *b' c g f'*, thus assuming the instantaneous rise of roll train resistance to the full value T_2. For other cases, and particularly for tapered ingots, the "approach load" *a′ a c b′* must be investigated as a special problem. As the necessity for this will seldom arise, the complete solution will not be introduced at this time.

It may occur at this part of the treatment of the subject that an item of leading importance must be assumed or defined before analysis of the complicated phenomena can be undertaken. This item is the tangential force due to the roll pass, which can be obtained in two ways. First, by direct experiment on existing roll trains. Second, by calculation through the use of suitable formulæ and physical constants. Assuming that by some means a definite knowledge of the energy diagram for a given "pass" is available, the considerations governing the proportions of flywheels and motors may be developed from the dynamics of the problem. Energy diagrams for mill operations may be divided into two distinct classes, illustrated by Figs. 2 and 3. The former may characterize all isolated roll trains having individual motors, in which equipment there is no possibility of a simultaneous operation in two or more grooves.

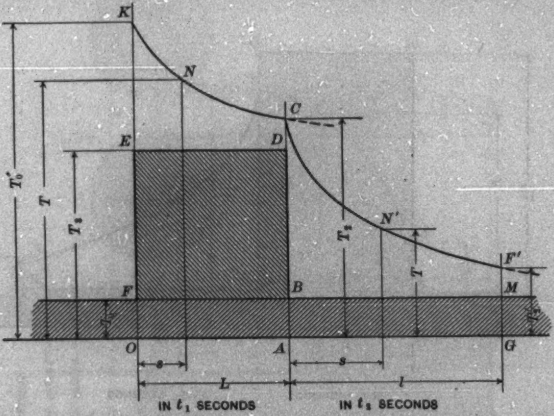


TYPE I—Tangential force at the motor shaft at the instant of full entry of bar into the pass is *less* than the tangential force due to the roll train resistance, *i.e.*, $T_0' < T_2$

FIG. 2—Elementary load. Rigid roll connection.

The roll "passes", so far as time of action is concerned, are completely isolated.

The latter (Fig. 3) may develop in systems of rolls driven from a lay shaft and gearing such that the simultaneous action on two or more "passes" is a possibility. This action results in certain "combination loads". The principal distinction between these energy diagrams consists of the following: The initial tangential force T_0' in Type I is less than T_2, due to the roll train, and generally greater than T_0, due to friction load. The force



TYPE II—Tangential force at the motor shaft at the instant of full entry of bar is *greater* than the tangential force due to the roll train resistance, *i.e.*, $T_0' > T_2$

FIG. 3—Elementary load. Rigid roll connections.

T_0' for Type II is greater than T_2 by virtue of the previous history of the motor action, and is invariably the result of combination loads of a certain class. Equations (1) to (36), inclusive, exhibit the dynamical relations for these elementary loads.

CYCLICAL OPERATION OF ROLL TRAINS

With all the apparent variations of load conditions in a given mill, there is for the same class of steel product a well defined cycle of operations into which the mill equipment and its operatives gravitate. The determination of the elements of this cycle, including forces in action, time intervals, etc., is capable of precision within the limits of error of the primary data, by means of equations (**1**) to (**36**) and the particularly important value of the force ${}_nT'_3$ at the end of the last time interval for a mill cycle. The derivation of the numerical value of this force from the elements of the various loads composing the cycle is shown in equations (**37**) to (**43**) inclusive.

It is seen that all the formulæ are dominated by a particularly important constant A, which embodies all that is characteristic of both motor and wheel, so far as the dynamics of the problem of roll driving are concerned. Its value must be determined with some degree of accuracy, since gross errors will vitiate all of the subsequent calculations.

As an independent check on the numerical value of A the diagram (Fig. 4) has been prepared with explanatory notes, such as to favor a rapid estimate through the use of a straight edge set in two consecutive positions. The positions of the straight edge conform to the fundamental items τ, Δ_τ, v_s, and $M K^2$.

These are constant for any given combination of motor and wheel, irrespective of the nature of mill loads to which they may be subject.

ANALYSIS OF ELEMENTARY LOADS SHOWN AS TYPE I AND TYPE II, ASSUMING RIGID ROLL CONNECTIONS

The energy diagram (Figs. 2 and 3) for the pass is area $O\,A\,D\,E$ of which $O\,A\,B\,F$ is the portion representing the friction load due to light running of the mill. The tangential force T due to motor, never goes below T_0 corresponding to the above friction load.

Area $K\,N\,C\,D\,E$	represents energy from the wheel for Type I load and to the wheel for Type II load.
Area $O\,F\,K\,N\,C\,A$	represents energy from the motor.
Area $B\,C\,N'\,F'\,M$	represents energy from the motor to the wheel during the interval between passes.
Area $A\,B\,M\,G$	represents energy due to friction load during the interval between passes.

Notation. All forces, velocities, lengths, and times are supposed to be reduced to the action at the extremity of the radius of one foot at the motor shaft.

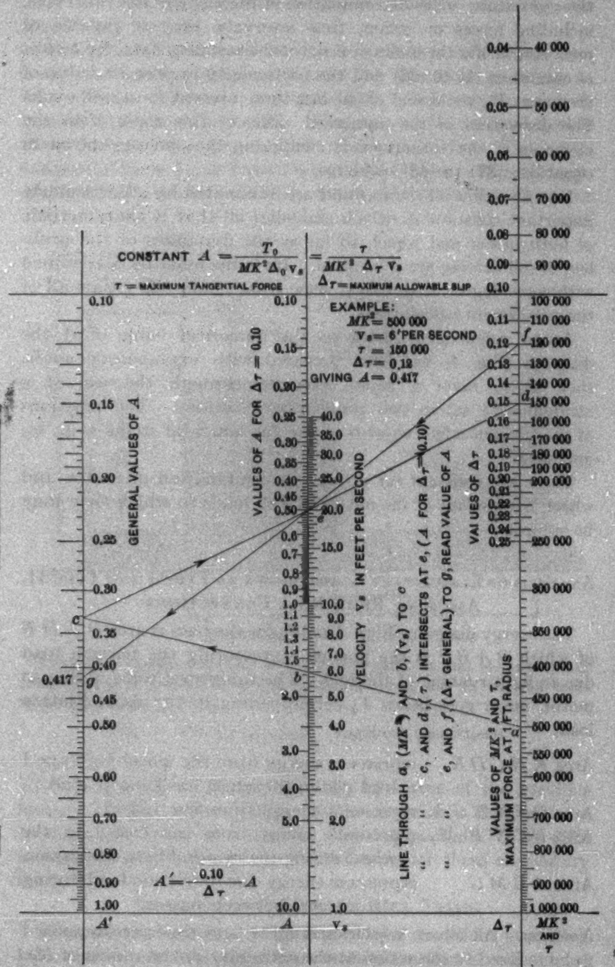

CONSTANT $A = \frac{T_0}{MK^2 \Delta_0 v_s} = \frac{\tau}{MK^2 \Delta_\tau v_s}$
τ = MAXIMUM TANGENTIAL FORCE
Δ_τ = MAXIMUM ALLOWABLE SLIP
EXAMPLE:
$MK^2 = 500\,000$
v_s = 6' PER SECOND
$\tau = 150\,000$
$\Delta_\tau = 0.12$
GIVING $A = 0.417$
GENERAL VALUES OF A
VALUES OF A FOR $\Delta_\tau = 0.10$
VELOCITY v_s IN FEET PER SECOND
LINE THROUGH a, (MK^2) AND b, (v_s) TO c
" " c, AND d, (τ) INTERSECTS AT e, (A FOR $\Delta_\tau = 0.10$)
" " e, AND f, (Δ_τ GENERAL) TO g, READ VALUE OF A
VAI UES OF Δ_τ
VALUES OF MK^2 AND τ, MAXIMUM FORCE AT 1 FT. RADIUS
$A' = \frac{0.10}{\Delta_\tau} A$
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.417
0.45
0.50
0.60
0.70
0.80
0.90
1.00
A'
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
2.0
3.0
4.0
5.0
10.0
A
40.0
35.0
30.0
25.0
20.0
15.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
v_s
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
Δ_τ
40 000
50 000
60 000
70 000
80 000
90 000
100 000
110 000
120 000
130 000
140 000
150 000
160 000
170 000
180 000
190 000
200 000
250 000
300 000
350 000
400 000
450 000
500 000
550 000
600 000
700 000
800 000
900 000
1 000 000
MK^2 AND τ
a
b
c
d
e
f
g

FIG. 4—Diagram for calculating constant *A*

K = Ratio of radius of gyration to unity for the wheel and rotating part of the motor combined.
M = Combined mass of the wheel and rotor.
L = Length of feet corresponding to the pass.
l = Length in feet corresponding to the interval.
t_1 = Time in seconds to complete the pass.
t_2 = Time in seconds to cover the interval.
v_s = Velocity corresponding to synchronous speed, ft. per sec.
v_0 = Velocity at friction load, ft. per sec.
v_1 = Velocity at the end of the pass, ft. per sec.
v_0' = Velocity corresponding to the initial force T_0'.
v = Velocity at any intermediate distance s and time t.
T = Tangential force at any instant t and distance s, pounds
T_0 = Tangential force corresponding to friction load, pounds.
T_0' = Tangential force at start of the pass, pounds.
T_1 = Tangential force at end of the pass, pounds.
T_2 = Tangential force at beginning of the interval, pounds.
T_2' = Tangential force at end of the interval, pounds.
T_3 = Tangential force due to the roll train resistance, pounds.

Type I. Relations for the Pass. From the general assumption that the decrease of velocity of the rotor, *i.e.*, the "slip" is proportional to the tangential force at unit radius, we have

$$T : T_0 :: v_s - v : v_s - v_0$$

or

$$T = \frac{T_0}{v_s - v_0} \left(v_s - \frac{d\,s}{d\,t}\right) \ldots\ldots\ldots \quad (1)$$

from this

$$\frac{d\,T}{d\,t} = -\frac{T_0}{v_s - v_0} \cdot \frac{d^2 s}{d\,t^2} \ldots\ldots\ldots\ldots (2)$$

The force acting on the roll train, due to the change of speed of the fly-wheel, acts in the same direction as the effort of the motor T and has a value $-M K^2 \frac{d^2 s}{d\,t^2}$ whence,

$$T - M K^2 \frac{d^2 s}{d\,t^2} = T_3 \quad \ldots\ldots\ldots\ldots\ldots (3)$$

observing the value in (**2**) we obtain,

$$\frac{d\,T}{d\,t} + \frac{T_0}{M\,K^2\,(v_s - v_0)} \cdot T = \frac{T_0}{M\,K^2\,(v_s - v_0)} \cdot T_3 \quad \ldots (4)$$

which will be written,

$$\frac{d\,T}{d\,t} + A\,T = A\,T_3 \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The integrating factor of this is ε^{At}, leading to,

$$T = T_3 + c \cdot \varepsilon^{-At} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

when $t = 0$, then $T = T_0'$ and $c = T_0' - T_3$. . . . . (**7**)

i.e.

$$t = \frac{1}{A} \log_\varepsilon \left(\frac{T_3 - T_0'}{T_3 - T} \right) \quad \ldots\ldots\ldots\ldots\ldots (8)$$

The time for the pass is therefore,

$$t_1 = \frac{1}{A} \log_\varepsilon \left(\frac{T_3 - T_0'}{T_3 - T_2} \right) \ldots\ldots\ldots\ldots\ldots (9)$$

which becomes infinite for $T_2 = T_3$.

In practical applications it is frequently convenient to employ the approximate value

$$t_1 = \frac{L}{v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Returning to (**1**) and (**3**) we have,

$$-M\,K^2 \frac{d^2\,s}{d\,t^2} + \frac{T_0}{v_s - v_0} \left(v_s - \frac{d\,s}{d\,t} \right) = T_3 \quad \ldots (11)$$

or

$$\frac{d^2\,s}{d\,t^2} + A\,\frac{d\,s}{d\,t} = A\,v_s - \frac{T_3}{M\,K^2} \quad \ldots\ldots\ldots (12)$$

$$= A \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right]$$

Considering $\frac{d\,s}{d\,t}$ as the variable we have,

$$\frac{d\,s}{d\,t} = v_s - \frac{T_3}{T_0}(v_s - v_0) + c_1 \cdot \varepsilon^{-At} \quad \ldots\ldots\ldots (13)$$

when $t = 0$, then $\frac{d\,s}{d\,t} = v_0{}' = v_s - \frac{T_0{}'}{T_0}(v_s - v_0)$

and

$$c_1 = (v_s - v_0)\frac{T_3 - T_0{}'}{T_0} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

$$\therefore\ \frac{d\,s}{d\,t} = v_s - \frac{T_3}{T_0}(v_s - v_0) + (v_s - v_0)\frac{T_3 - T_0{}'}{T_0} \cdot \varepsilon^{-At} \quad (15)$$

also

$$s = \left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right] t - (v_s - v_0)\frac{T_3 - T_0{}'}{A\,.\,T_0} \cdot \varepsilon^{-At} + c_2 \quad (16)$$

when $t = 0$, then $s = 0$, and $c_2 = (v_s - v_0) . \frac{T_3 - T_0{}'}{A\,T_0} \ldots\ldots (17)$

Finally:

$$s = \left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right] \cdot t + (v_s - v_0)\,(1 - \varepsilon^{-At}) . \frac{T_3 - T_0{}'}{A\,T_0} \quad (18)$$

Substituting the value of t from (8) in equation (18)

$$s = \frac{1}{A}\left\{\left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right]\log_e\left(\frac{T_3 - T_0{}'}{T_3 - T}\right) + (v_s - v_0)\frac{T - T_0{}'}{T_0}\right\} \quad (19)$$

Length of pass

$$L = \frac{1}{A}\left\{\left[v_s - \frac{T_3}{T_0}(v_s - v_0)\right]\log_e\left(\frac{T_3 - T_0{}'}{T_3 - T_2}\right) + (v_s - v_0)\frac{T_2 - T_0{}'}{T_0}\right\} \quad (20)$$

Types I and II. Relations for the Interval Between Passes. At the point N' with A as origin,

$$T - T_0 - M K^2 \frac{d^2 s}{d t^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots (21)$$

Substituting the value of $\frac{d^2 s}{d t^2}$ from (**2**)

$$\frac{d T}{d t} + A T = A T_0 \quad \ldots\ldots\ldots\ldots\ldots (22)$$

leading to,

$$t = \frac{1}{A} \log_e \left(\frac{T_2 - T_0}{T - T_0} \right) \quad \ldots\ldots\ldots\ldots\ldots (23)$$

and

$$t_2 = \frac{1}{A} \log_e \left(\frac{T_2 - T_0}{T_2' - T_0} \right) \qquad (24)$$

Also from (1) and (21)

$$\frac{d^2 s}{d t^2} + A \frac{d s}{d t} = A v_0 \qquad (25)$$

leading to,

$$\frac{d s}{d t} = v_0 - (v_s - v_0) \left(\frac{T_2 - T_0}{T_0} \right) \cdot \varepsilon^{-At} \quad \ldots\ldots\ldots (26)$$

$$s = v_0 t + \left(\frac{v_s - v_0}{A} \right) \left(\frac{T_2 - T_0}{T_0} \right) (\varepsilon^{-At} - 1) \quad \ldots\ldots (27)$$

Substituting the value of t from (**23**)

$$s = \frac{1}{A} \left\{ v_0 \log_e \left(\frac{T_2 - T_0}{T - T_0} \right) - \frac{T_2 - T}{T_0} (v_s - v_0) \right\} \quad \ldots (28)$$

For particular values

$$l = \frac{1}{A} \left\{ v_0 \log_e \left(\frac{T_2 - T_0}{T_2' - T_0} \right) - (v_s - v_0) \frac{T_2 - T_2'}{T_0} \right\} \quad \ldots . (29)$$

Type II. Relations for the Pass. The force acting on the fly-wheel is the excess of effort of the motor T above the resistance of the roll train T_3 and has a value $+ M K^2 \frac{d^2 s}{d t^2}$ whence,

$$T - T_3 - M K^2 \frac{d^2 s}{d t^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots . (30)$$

The differential equations derivable from (**1**), (**2**) and (**30**) are identical in form with (**22**) and (**25**), subject to the same treatment in integration; thus $T_0' > T_3$ we have

$$t = \frac{1}{A} \log_e \left(\frac{T_0' - T_3}{T - T_3} \right) \quad \ldots\ldots\ldots\ldots . (31)$$

$$t_1 = \frac{1}{A} \log_e \left(\frac{T_0' - T_3}{T_2 - T_3} \right) \quad \ldots\ldots\ldots\ldots\ldots . (32)$$

Similarly:

$$\frac{d s}{d t} = v_s - \frac{T_3}{T_0} (v_s - v_0) - (v_s - v_0) \frac{T_0' - T_3}{T_0} \cdot \varepsilon^{-At} \qquad (33)$$

and

$$s = \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \cdot t + (v_s - v_0) (\varepsilon^{-At} - 1) \left(\frac{T_0' - T_3}{A T_0} \right) \quad (34)$$

$$= \frac{1}{A} \left\{ \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \log_e \left(\frac{T_0' - T_3}{T - T_3} \right) - (v_s - v_0) \frac{T_0' - T}{T_0} \right\} \quad (35)$$

also

$$L = \frac{1}{A} \left\{ \left[v_s - \frac{T_3}{T_0} (v_s - v_0) \right] \log_e \left(\frac{T_0' - T_3}{T_2' - T_3} \right) - (v_s - v_0) \frac{T_0' - T_2}{T_0} \right\} \quad (36)$$

RELATION BETWEEN THE FORCES AND TIME INTERVALS FOR A MILL CYCLE—CYCLICAL ACTION

$$\text{from (9)} \quad T_2 = T_0' \cdot \varepsilon^{-At_1} + T_3\,(1 - \varepsilon^{-At_1}) \quad \ldots\ldots (37)$$

$$\text{from (24)} \quad T_2' = T_0'\,(1 - \varepsilon^{-At_2}) + T_2 \cdot \varepsilon^{-At_2} \quad \ldots\ldots\ldots (38)$$

$$= T_0\,(1 - \varepsilon^{-At_2}) + T_3\,(1 - \varepsilon^{-At_1})\,\varepsilon^{-At_2} + T_0'\,\varepsilon^{-A(t_1+t_2)} \quad (39)$$

This may be transformed into

$$T_2' \cdot \varepsilon^{A(t_1+t_2)} = T_0\,(\varepsilon^{At_2} - 1)\,\varepsilon^{At_1} + T_3\,(\varepsilon^{At_1} - 1) + T_0' \quad (40)$$

For clearness of notation let

$a = A\,t_1$ and $b = A\,t_2$ using a_1, a_2, etc., for the several passes, and b_1, b_2, . . . b_n for the successive intervals.

Then, for the several passes,

$$\left.\begin{aligned}
{}_1T_2' \cdot \varepsilon^{a_1+b_1} &= T_0\,(\varepsilon^{b_1} - 1)\,\varepsilon^{a_1} + {}_1T_3\,(\varepsilon^{a_1} - 1) + {}_1T_0' \\
{}_2T_2' \cdot \varepsilon^{a_2+b_2} &= T_0\,(\varepsilon^{b_2} - 1)\,\varepsilon^{a_2} + {}_2T_3\,(\varepsilon^{a_2} - 1) + {}_2T_0' \\
{}_3T_2' \cdot \varepsilon^{a_3+b_3} &= T_0\,(\varepsilon^{b_3} - 1)\,\varepsilon^{a_3} + {}_3T_3\,(\varepsilon^{a_3} - 1) + {}_3T_0' \\
\cdots\cdots\cdots &= \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
{}_{n-1}T_2' \cdot \varepsilon^{a_{n-1}+b_{n-1}} &= T_0(\varepsilon^{b_{n-1}} - 1)\varepsilon^{a_{n-1}} + {}_{n-1}T_3(\varepsilon^{a_{n-1}} - 1) + {}_{n-1}T_0' \\
{}_nT_2' \cdot \varepsilon^{a_n+b_n} &= T_0\,(\varepsilon^{b_n} - 1)\,\varepsilon^{a_n} + {}_nT_3\,(\varepsilon^{a_n} - 1) + {}_nT_0'
\end{aligned}\right\} \quad (41)$$

Bearing in mind that ${}_{n-1}T_2' = {}_nT_0'$ and finally ${}_nT_2' = {}_1T_0'$ for cyclical operation we have

$$\left.\begin{aligned}
{}_nT_2' = &\{T_0\,(\varepsilon^{b_n} - 1)\,\varepsilon^{a_n} + {}_nT_3\,(\varepsilon^{a_n} - 1)\} \cdot \varepsilon^{-(a_n+b_n)} \\
&+ \{T_0(\varepsilon^{b_{n-1}} - 1)\varepsilon^{a_{n-1}} + {}_{n-1}T_3(\varepsilon^{a_{n-1}} - 1)\} \cdot \varepsilon^{-(a_n+a_{n-1}+b_n+b_{n-1})} \\
&+ \{T_0(\varepsilon^{b_{n-2}}-1)\varepsilon^{a_{n-2}} + {}_{n-2}T_3(\varepsilon^{a_{n-2}}-1)\} \cdot \varepsilon^{-(a_n+a_{n-1}+a_{n-2}+b_n+b_{n-1}+b_{n-2})} \\
&+ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
&+ \{T_0(\varepsilon^{b_3}-1)\varepsilon^{a_3} + {}_3T_3(\varepsilon^{a_3} - 1)\} \cdot \varepsilon^{-(a_n+a_{n-1}\ldots+a_3+b_n+b_{n-1}+\ldots b_3)} \\
&+ \{T_0(\varepsilon^{b_2} - 1)\varepsilon^{a_2} + {}_2T_3\,(\varepsilon^{a_2} - 1)\} \cdot \varepsilon^{-(\Sigma_2^n a+\Sigma_2^n b)} \\
&+ \{T_0(\varepsilon^{b_1} - 1)\varepsilon^{a_1} + {}_1T_3(\varepsilon^{a_1} - 1)\} \cdot \varepsilon^{-(\Sigma_1^n a+\Sigma_1^n b)} \\
&+ {}_1T_0 \cdot \varepsilon^{-(\Sigma_1^n a+\Sigma_1^n b)}
\end{aligned}\right\} \quad (42)$$

Multiplying each side by $\varepsilon^{(\sum_1^n a+\sum_1^n b)}$ and transposing ${}_1T_0'={}_nT_2'$ we have

$$
{}_nT_2'\left(\varepsilon^{(\sum_1^n a+\sum_1^n b)}-1\right)=
$$

$$
\left.\begin{aligned}
&\{T_0(\varepsilon^{b_n}-1)\cdot\varepsilon^{a_n}+{}_nT_3(\varepsilon^{a_n}-1)\}\cdot\varepsilon^{(\sum_1^{n-1}a+\sum_1^{n-1}b)}\\
&+\{T_0(\varepsilon^{b_{n-1}}-1)\cdot\varepsilon^{a_{n-1}}+{}_{n-1}T_3(\varepsilon^{a_{n-1}}-1)\}\cdot\varepsilon^{(\sum_1^{n-2}a+\sum_1^{n-2}b)}\\
&+\{T_0(\varepsilon^{b_{n-2}}-1)\cdot\varepsilon^{a_{n-2}}+{}_{n-2}T_3(\varepsilon^{a_{n-2}}-1)\}\cdot\varepsilon^{(\sum_1^{n-3}a+\sum_1^{n-3}b)}\\
&+\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\\
&+\{T_0(\varepsilon^{b_3}-1)\cdot\varepsilon^{a_3}+{}_3T_3(\varepsilon^{a_3}-1)\}\cdot\varepsilon^{(a_1+a_2+b_1+b_2)}\\
&+\{T_0(\varepsilon^{b_2}-1)\cdot\varepsilon^{a_2}+{}_2T_3(\varepsilon^{a_2}-1)\}\cdot\varepsilon^{a_1+b_1}\\
&+\{T_0(\varepsilon^{b_1}-1)\,\varepsilon^{a_1}+{}_1T_3(\varepsilon^{a_1}-1)\}
\end{aligned}\right\}\quad(\mathbf{43}).
$$

The above equations (**40**) to (**43**) inclusive, are general for type loads (I) and (II) with any value of the time intervals including t_2 (equation **24**) equal to zero. They, consequently, form the basis of calculating the starting force T_0' for the first pass in a mill cycle; even for combination loads.

Suppose $\varepsilon^a = 10.^{\alpha}$ Then $a\log_{10}\varepsilon = \alpha$

But

$$\log_{10}\varepsilon = 0.4343$$

$$\therefore\ 0.4343\,a = \alpha$$

and we may write

$$\varepsilon^a = 10^{\cdot\alpha} = 10^{\cdot 0.4343a}$$

Hence, if we multiply each of the above exponents by 0.4343 and replace $\varepsilon = 2.71828$ by 10 we may employ the ordinary system of logarithms in the above calculations. This process may be completed once for all if we say,

$$a = 0.4343\,A\,t_1$$

$$b = 0.4343\,A\,t_2$$

Thus leading to the following system of equations for calculating ${}_nT_2'$ *viz.*,

$$
\left.
\begin{aligned}
&{}_nT_2' \left(10^{(\sum_1^n a + \sum_1^n b)} - 1\right) = \\
&\quad \{T_0 (10^{b_n} - 1) \cdot 10^{a_n} + {}_nT_3 (10^{a_n} - 1)\} \cdot 10^{(\sum_1^{n-1} a + \sum_1^{n-1} b)} \\
&+ \{T_0 (10^{b_{n-1}} - 1) \cdot 10^{a_{n-1}} + {}_{n-1}T_3 (10^{a_{n-1}} - 1)\} \cdot 10^{(\sum_1^{n-2} a + \sum_1^{n-2} b)} \\
&+ \{T_0 (10^{b_{n-2}} - 1) 10^{a_{n-2}} + {}_{n-2}T_3 (10^{a_{n-2}} - 1)\} \cdot 10^{(\sum_1^{n-3} a + \sum_1^{n-3} b)} \\
&+ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
&\quad \{T_0 (10^{b_3} - 1) 10^{a_3} + {}_3T_3 (10^{a_3} - 1)\} \cdot 10^{(a_1 + a_2 + b_1 + b_2)} \\
&\quad \{T_0 (10^{b_2} - 1) \cdot 10^{a_2} + {}_2T_3 (10^{a_2} - 1)\} \cdot 10^{(a_1 + b_1)} \\
&\quad \{T_0 (10^{b_1} - 1) \cdot 10^{a_1} + {}_1T_3 (10^{a_1} - 1)\}
\end{aligned}
\right\} \quad (44)
$$

The influence of the exponential terms is such that it is usually unnecessary to employ more than the first three or four terms in the series for the calculation of the starting force (${}_nT_2' = {}_1T_0'$).

ENERGY FROM THE MOTOR

From (1)

$$d\,s = \left(v_s - \frac{T}{T_0}(v_s - v_0)\right) d\,t \quad \ldots\ldots\ldots \quad (1a)$$

from (5) or (8)

$$d\,t = \frac{1}{A} \cdot \frac{d\,t}{T_3 - T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (45)$$

from (22) or (23)

$$d\,t = \frac{1}{A} \cdot \frac{d\,T}{T_0 - T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (46)$$

from (1a) and 45

$$d\,s = \frac{1}{A}\left[v_s - \frac{T}{T_0}(v_s - v_0)\right] \cdot \frac{d\,T}{T_3 - T} \quad \ldots\ldots\ldots \quad (47)$$

The energy from the motor during the pass in foot pounds is,

$$\int_0^L T\,d\,s = \frac{1}{A}\int_{T_0'}^{T_2}\left[v_s - \frac{T}{T_0}(v_s - v_0)\right]\frac{T\,d\,T}{T_3 - T} \quad \ldots\ldots \quad (48)$$

$$= \frac{1}{A}\left\{\left[(v_s - v_0)\frac{T_3}{T_0} - v_s\right]\left[T_2 - T_0' + T_3 \log_e \frac{T_3 - T_3}{T_3 - T_2}\right] + (v_s - v_0)\,\frac{T_2^2 - (T_0')^2}{2\,T_0}\right\} \quad \ldots\ldots\ldots \quad (49)$$

Substituting the value of L from (**20**)

$$\int_0^L T\,ds = T_3 L - \frac{1}{A}(T_2 - T_0')\left[v_s - \frac{T_2 + T_0'}{2\,T_0}(v_s - v_0)\right] \quad \textbf{(50)}$$

Similarly, from (**1a**), (**46**) and (**29**) we obtain:
The energy from the motor during the interval in foot pounds

$$\int_0^l T\,ds = T_0\,l + \frac{1}{A}(T_3 - T_2')\left[v_s - \frac{T_3 + T_2'}{2\,T_0}(v_s - v_0)\right] \quad \textbf{(51)}$$

In view of the following statements equations (**54**) and (**55**) we may say:

$$\int_0^L T\,ds = T_3 L - \frac{M\,K^2}{\tau}\Delta_\tau\,v_s^2\,(T_2 - T_0')\left[1 - \frac{T_2 + T_0'}{2\,\tau}\Delta_\tau\right] \quad \textbf{(50a)}$$

$$\int_0^l T\,ds = T_0\,l + \frac{M\,K^2}{\tau}\Delta_\tau\,v_s^2\,(T_3 - T_2')\left[1 - \frac{T_3 + T_2'}{2\,\tau}\Delta_\tau\right] \quad \textbf{(51a)}$$

$$\int_0^L Tds + \int_0^l Tds = T_3\,L + T_0\,l + \frac{M\,K^2}{\tau}\Delta_\tau v_s^2\,(T_0' - T_2')$$

$$\left[1 - \frac{T_0' + T_2'}{2\,\tau}\Delta_\tau\right] \quad \textbf{(51b)}$$

NOTE ON THE VALUE OF THE CONSTANT A

$$A = \frac{T_0}{MK^2(v_s - v_0)} = \frac{T_0\,\frac{v_s + v_0}{2}}{\frac{1}{2}M(K^2 v_s^2 - K^2 v_0^2)} = \frac{1}{\theta} \quad \ldots.\textbf{(52)}$$

where θ is a time in seconds.
Thus: θ is time required for the force T_0 acting with a mean velocity $\frac{v_s + v_0}{2}$ to deliver the energy corresponding to that absorbed by the wheel when the velocity v_0 is increased to v_s, *i.e.*,

$$\frac{1}{2}\,M\left[K^2 v_s^2 - K^2 v_0^2\right] = T_0\,\theta\,\frac{v_s + v_0}{2} \quad \ldots\ldots..\textbf{(53)}$$

Assuming that the nature of roll train loads gives evidence of the maximum tangential force τ which will be imposed on the motor, and that the corresponding velocity is v_τ, then equation (**1**) gives

$$\tau : T_0 :: v_s - v_\tau : v_s - v_0$$

i.e.,

$$v_s - v_0 = \frac{T_0}{\tau} (v_s - v_\tau) = \frac{T_0}{\tau} \triangle_\tau v_s \tag{54}$$

where $\triangle_\tau$ is the maximum allowable slip in per cent of synchronous speed corresponding to the maximum force τ whence from (**52**) and (**54**)

$$A = \frac{\tau}{M K^2 \triangle_\tau v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \tag{55}$$

While the commercially advisable slip for a given equipment of power plant motors and transmission lines is always a local problem, it seems to be the evidence of recent large installations that $\triangle_\tau$ lies in value between 0.08 and 0.12 and may be accepted in preliminary designs at $\triangle_\tau = 0.10$ whence

$$A = \frac{10 \tau}{M K^2 v_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \tag{56}$$

DISCUSSION ON "INTERACTION OF FLYWHEELS AND MOTORS WHEN DRIVING ROLL TRAINS BY INDUCTION MOTORS." JEFFERSON N. H., JUNE 29, 1910.

C. P. Steinmetz: This paper of Mr. Gasche I consider a very valuable and important addition to the records of our Institute dealing as it does with an extremely important problem of motor application, an application, indeed, which I believe represents the most severe service to which electric motors have ever been applied.

When we speak of intermittent load or fluctuating load, usually we immediately think of railway loads. We realize that the load mathematically discussed in this paper, the roll train, is a load in which the fluctuation is vastly more rapid and more violent than in any railway train. I understand that under certain conditions the change from friction load to maximum load, and return to friction load, occurs within less than one revolution of the driving motor. The system which is dealt with in the paper is a system of a power consuming device, the roll train, in which power is consumed at a very fluctuating rate, but with fluctuations which are fairly definite in their nature, a power supply at a rate by which speed and power are related to each other in the well known manner of the induction motor, and the energy storing device, the flywheel. Here we have changes in the condition of the system at such a rate that never during the operation do the conditions, in regard to speed and torque of the motor become constant, that is, the phenomenon with which we have to deal here is not that of stationary operation but is a transient operation, and again here we are in the field of transient phenomena, and if we look at the equations we will recognize immediately the transient function as characterizing the inter-relation of phenomena. Now, transients have one characteristic, that is, the relation of the elements to the system are not determined by their constants alone, but are also determined and dependent on the conditions of the system at the starting moment and at the end of the transition, that is, the so-called terminal conditions enter into the function mathematically as integration constants.

Now, we have two different forms into which the terminal conditions enter, either as independent and fixed conditions, or as relations connecting the conditions of the system, at the starting moment and at the finishing moment of the cycle. For instance, if an electrical circuit is changed by a switch, you have given the previous condition and you have given the final condition, between these two the transient completes its course. A second case is where the terminal condition is related to the starting condition, usually identical therewith, that means where the transient condition recurs as recurrent transient phenomenon. Recurrent transients, as you know are used in the electrical industry to a large extent for circuit control—in the circuit control which cuts resistance in and out of the motor field periodically. Such recurrent transients are the arcing grounds which we have on our transmission lines, etc.

The recurrent transient which Mr. Gasche treats of so interestingly in this paper is a very much more complex one. The cycle completes, not after two or three steps, as we usually find, but after a very great number of steps, during the passing of the roll train, each being characterized by a rapid change, from friction load to maximum load and back to friction load, next passing from friction load to maximum load, possibly smaller or longer duration than the previous one, back again to friction load, and so on, until finally the cycle closes itself by the last terminal condition coinciding with the first starting point.

This is extremely interesting, and as we all realize, it is a very important problem which is here dealt with. Interesting and important also the subject is, as pointed out by Mr. Gasche in his opening remarks, in another respect—by the nature of the load. The loads here consist of the action of forces within that range from which scientists and theoretical investigators usually keep carefully away, while industrially it is the range of greatest importance, that is, the range beyond the elastic limit, where the action of the forces has become irreversible. We have already spent some time at this convention in studying the range of electric forces at those voltages where the action has become irreversible, where we are beyond the elastic limit of the action of electric field.

Here you have the condition before you when you deal with mechanical forces acting beyond the elastic limit.

We cannot expect too much at once, but I hope you will join with me in expressing the wish that Mr. Gasche may find it possible very soon to complete this valuable information by giving us what is referred to, how to calculate that maximum load by the use of suitable formula and physical constants. It is a field which is of extreme importance, not only in the range of mechanical forces, but also in the range of electrical forces, and all other forces, because here we get information on the nature of the forces, where you are beyond the elastic limit, and it is in this field which is being opened up at present, and up to the door of which the present paper leads and, as we hope, the next paper of Mr. Gasche will lead us beyond the door into the field of that development.

Charles F. Scott: We are always interested to see electricity do big things and new things—our interest in connection with the steel mill has been to see the motor take the place of the engine, the engine which has been capable of quick reversing and handling enormous instantaneous loads. The thing which struck me particularly, as Mr. Gasche was giving the introduction to his paper, and indicating some of the conditions which he has to meet, were the features which lead away from what has been done before—he was not simply replacing the engine, which used to do something ponderous and impressive, but he was going into an entirely different field and doing something which had not been done before, and something which could not be done before.

The little electric motor which only a dozen years ago was an average street railway motor of 25 or 50 h.p., doing some auxiliary features about the mill and was looked on as a kind of toy, entirely insignificant compared with the main operations of the mill—that little motor has grown until it has become the central feature of the steel industry. Take the power plant—that has changed, we have a new kind of prime mover, one which is not at all adapted to steel mill work, a gas engine, which is a great big, slow moving, constant running, non-overload machine, just the kind of thing that is not fitted for the intermittent speed and power requirements of steel mills.

Going to the other extreme, the requirements in the way of rolls and performance are, as Mr. Gasche points out, simply enormous in the operations of a steel mill; they have never been met before, and in between this otherwise helpless, big, gas engine and these tremendous requirements in the rolls, comes the electric system with the motor, and with one of the simplest kinds of motors, the induction motor. The alternating current generator and the induction motor, the simplest types of generator and motor, come in to perform this marvelous service which is revolutionizing the whole steel business.

The power problem is, as Dr. Steinmetz pointed out, one of the most severe problems which appears in mechanical work. In one sense the problem is of a very elementary kind, in that it does not go into the unknown and involve mysterious features such as some of these electrical discussions that we have had today, involving ions, gases, and one thing and another, but in the rather long table of the symbols which enter into the formulæ we have simply those which represent the most elemental matters in mechanics. There is mass, and length, and time, the fundamental units, and then there is a little more complexity in the case of velocity, etc., and the problem is simply, we may say, the elementary mechanical problem of supplying the proper constants and working out the mechanical elements, which in turn will give the motor requirements, the speed and torque, or tangential forces to be developed by the motor. It is by this kind of language that the requirements of service can be gotten into the nomenclature of the motor, which is simply torque and speed.

To read a paper and hear explanations of these new large forces and requirements is impressive, but it is still more impressive to see the thing itself. In looking at the reversing motors in the South Chicago works of the Illionois Steel Company some time ago, I was very much impressed in standing and looking at the motor and its great big armature, some five feet in diameter, revolving rapidly in one direction, and then easily and quietly and quickly reversing and running in the other direction, and oscillating back and forth under the control of the little hand lever of the distant operator; and yet that motor and those rolls can reverse, from 4800 kw. in one direction to the same amount in the other direction, in six seconds—and the motor-generator set which supplies the power for variations of that kind, for the loads thrown on and off as the ingot comes in and out of the rolls, is such that the power that is taken from the generator is practically constant within a variation of 25 or 30 per cent. These enormous powers, the ease with which these sudden changes take place, and yet the practical constancy on the circuit, are something to observe, and cause a new wonder and admiration for what electricity has accomplished.

Gano Dunn: Mr. Gasche's work may be regarded in one respect as looking toward the development of a substitute for the storage battery. A few years ago there was brought out, the value of batteries floating on the line to serve as reservoirs of power and to absorb fluctuations. Such batteries enabled large reductions in plant capacity and in line, and enabled great improvements in regulation. Storage batteries, however, are not adapted to the excessively severe service and difficult environment of steel mills for the reason, as Mr. Edison more emphatically than is here permitted, used to put it, that they are wet.

While it is true that we have been familiar with the capacity of a flywheel for storing energy, we have never in the past made such general use of this property as has been recently made in steel mills in Europe and in this country. We have all known that a flywheel running at a constant speed can never deliver or absorb power and that it is only when we slow it down that we can uncover and make it give up the energy stored in it. We have also known the law of the rate at which it gives up its energy or absorbs it, but it has been left for Mr. Gasche to develop and analyze this law when the flywheel is electrically tied to a motor on the one hand, and rolling mill work on the other.

With Mr. Gasche's formulas we have spread out before us, all the necessary relations between motor, wheel and work, that we need to know in making use of the flywheel as a reservoir of energy and as a mechanical substitute for the electrical storage battery.

In sympathy with the paper, I criticize the statement "It will be shown in what follows, that on the assumption of perfectly rigid roll train connections and a rotor without any inertia effect (if such were possible), the induction motor is physically incapable of assuming any roll train load above the friction load that by some means may have been imposed on the motor."

I cannot agree with this. Up to the limit of its break-down torque the motor would accept load even if its rotor had no inertia, and I see no characteristic in the load that would be imposed by the entering of an ingot, that would introduce new conditions that would alter this fact.

The paper also says, "On the larger sizes of roll trains the shock imposed on the rolls and connections due to the action of a powerful motor of small slip, would prove such a destructive agent that the experience would be at least a costly one. The nature of the shock arising at the motor shaft can be understood from the following study of the characteristics of a roll pass."

The shock on the shaft of a big induction motor with small slip can be no greater than the shock on the shaft of the same motor when it has been equipped with a flywheel. The conclusion may follow from the formulas, but the formulas are good only within the scope of their terms, and the ideal case of a rotor with no inertia is probably not properly represented in this case, by the terms.

How much power to take out of a given wheel or how much of a wheel to install for a given power involves a nice consideration of first cost on one hand and annual charges on the other. The key to the problem is the percentage of slow-down.

For moderate slow-downs the energy a wheel will deliver is approximately proportional to twice the slow-down, while the energy wasted by the rotor of the induction motor driving it is roughly proportional to three times the slow-down.

With fixed slip resistance large slips or slow-downs, while involving cheap wheels, mean low efficiencies; and low efficiencies must be charged not only with the power wasted, but with their proportion of the increase in first cost of the plant to supply them. My experience has been that it is really cheaper to put in what at first looks like an expensive wheel and run it at small slip, even where power is cheap. This is dictated by reasons not only of economy but of effective operation, since regulation problems are simpler with small slips and overloads are less disturbing.

Where the flywheel installation absorbs a small proportion of the total output of the power plant of a mill, gradient of load change is of more importance than percentage of fluctuation between maximum and minimum load. For usual mill conditions, which involve relatively long waits between slabs or ingots compared to the waits between the passes of a given slab or ingot, what might be termed the maximum average power consumption is bound to occur almost no matter how big a flywheel is put in.

Even an enormously large flywheel will not continue to absorb power during the whole of the relatively long waits between slabs or ingots, nor will it deliver stored power during the whole of the relatively long time required for the succession of passes of any given slab or ingot. Consequently the main power plant must be installed to supply the maximum average power required by the work.

The flywheel's duty is to prevent fluctuations from this maximum average rather than from the datum line of zero power and if this view is taken, a moderate flywheel outfit, without attempting to smooth out the fluctuations that occur between successive slabs or ingots, will very satisfactorily smooth out the fluctuations occuring between the passes of a given slab or ingot.

In designing such moderate flywheels the gradient of the fluctuation rather than its absolute amount is the feature to which attention should be given. It is too sharp a gradient that causes noticeable change in the brilliancy of lamps. It is too sharp a gradient that causes synchronous apparatus in the neighborhood to drop out of step. It is too sharp a gradient that upsets the stability of governors in the power house and it is too sharp a gradient that prevents a happy and comfortable adjustment of all the apparatus in the mill to such rises and falls of potential as will occur in the everyday working of a steel mill.

If the gradient is properly taken care of, relatively large fluctuations of power may be permitted and in the ordinary large mill, where there are a number of fluctuating loads, these loads will be found to pool their demand for power so that the fluctuation from the power plant will be surprisingly small.

Where there is opportunity for pooling, it is a useless investment to install flywheels larger than just enough to prevent wide departures from the maximum average rolling load.

Selby Haar: Mr Gasche's paper is of great value at the present time, because it deals with a subject on which there are practically no data on record, so that all engineering recommendations on driving motors must be based on laborious calculation. For this reason, any conception which gives one a broader view of the problem is welcome.

The author has assumed that the torque of the motor is proportional to its slip. The same assumption underlies Mr. H. C. Specht's paper which was read at the Frontenac meeting. This does not affect the nature of the conclusions which have been drawn, and is an almost necessary simplification, but since the torque of an induction motor is not exactly proportional to the slip the variation must frequently be considered, especially if the maximum reduction in speed is specified. The writer has selected a set of conditions and drawn the torque curves to show this.

In Fig. 1, the full line shows the actual torque curve of a motor designed to give twice full load torque at 15 per cent slip; the dotted line represents a curve with the same slip at light load as the full line, while the dot and dash line is drawn so as to show the same torque at 15 per cent slip as the full line.

Fig. 2 shows the distribution of the duty between motor and flywheel corresponding to each of the torque curves. The full line curve was calculated by a method which will be described later, but equations 8 and 23 were used for the other two. Attention is called to the shape of the full line curve for the interval between passes. This is due to the departure of the torque curve from a straight line.

The method of calculation to which reference has been made was developed for rapid work without the aid of any tools but a slide rule after the torque curve is drawn. The theoretical basis is as follows:

T_3 is the total torque to be delivered.
T_a is the motor torque at the time t_a.
T_b the torque at the time t_b.

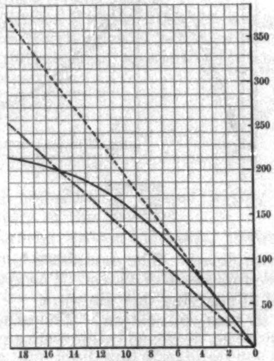


FIG. 1

From the torque curve we get σ_a as the slip corresponding to T_a and σ_b corresponding to T_b. This gives a difference in speed of $(1-\sigma_b)\,v_s-(1-\sigma_a)\,v_s$, and an average acceleration (or retardation) of $-\dfrac{(\sigma_b-\sigma_a)\,v_s}{t_b-t_a}$. The flywheel torque is

$$\frac{M\,K^2\,(\sigma_b-\sigma_a)\,v_s}{t_b-t_a}.$$

Then

$$\frac{T_a+T_b}{2}=T_3-M\,K^2\,\frac{(\sigma_b-\sigma_a)\,v_s}{t_b-t_a}\text{ for the pass,}$$

and

$$t_b - t_a = \frac{(\sigma_b - \sigma_a)\, v_s\, M K^2}{T_s - \dfrac{T_a + T_b}{2}}$$

Assuming constant intervals for $\sigma_b - \sigma_a$, say one per cent, we obtain $t_b - t_a$ directly. These times need only be summed until the pass is completed. The modification of the formula for the interval between passes is obvious. The attached tabulation shows the method of carrying out the work.

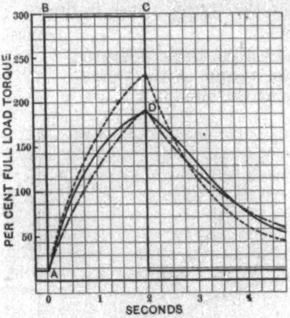


FIG. 2

Another point in this connection: The area *A*, *B*, *C*, *D*, *A* in Fig. 2 represents the decrease in momentum of the flywheel.

Pass.

Slip	T_a	T_b	$\frac{T_a+T_b}{2}$	$T_s - \frac{T_a+T_b}{2}$	$t_b - t_a$	Elapsed time
0.0055–0.01	15000	26500	20800	394200	0.042	0.042
0.01 –0.02	26500	53500	40000	375000	0.098	0.140
0.02 –0.03	53500	78500	66000	349000	0.105	0.245
0.03 –0.04	78500	104000	91200	323750	0.113	0.358

etc.

This can be separated into various factors of mass and speed drop until satisfactory division is obtained. It can be used as a check on the other method, or if the point *D* is fixed and the curve *A D* drawn in by estimation, the flywheel effect required can be determined directly.

W. W. Crawford (by letter): In discussing Mr. Gasche's paper, it is my purpose to call attention to some of the physical aspects of the interactions covered by his equations, to introduce a short-cut method for deriving the behavior of the apparatus under repeated cyclical loads from its behavior during the first cycle, and to extend the method to cases where regulating devices are used to control the torque of the motor.

The motor operates at constant speed under a constant friction torque until the first bloom reaches the rolls. This applies a sudden, but uniform, load. The motor then approaches a new condition of steady running, which, if the time required for the pass were sufficiently long, the motor would eventually reach. The approach to steady running is retarded by the inertia of the flywheel. The rapidity of the approach is less, the heavier the flywheel, and the greater the necessary increase in slip before the motor will take up the entire torque.

Mr. Gasche's equation 8 shows that the motor torque follows a logarithmic curve which approaches asymptotically to a line representing the uniform load applied. This equation may be put in the following form:

$$\operatorname{Log} \frac{T'}{T} = A\, t$$

where T' = initial unbalanced torque acting to change the velocity of the flywheel.
T = unbalanced torque at a later instant.
t = time interval.
A = a constant inversely proportional to the amount of inertia of the flywheel, and inversely proportional to the amount of slip for a given load.

When the load is removed, the motor is developing a torque in excess of the friction load, and the difference is an unbalanced torque accelerating the flywheel. The law of torque variation is the same (see equation 24) as before, when T' and T are taken to represent the unbalanced torques.

Therefore the calculation of any cycle resolves itself into considering the unbalanced torque at the beginning of each element of the cycle, computing from it the final unbalanced torque by means of the formula, and combining this with the rolling torques to obtain the motor torques. The same formula is used in each element since A is constant throughout.

A table of values of the ratio $\frac{T'}{T}$ corresponding to the different time intervals can be made up for a given set of rolls, and the same table will apply for the calculation of any combination of loads to which the apparatus may be subjected.

Calculation by the above method requires that the conditions at some point, say the beginning of the cycle, are known. Where the mill operation is continuous, conditions at the beginning of a given cycle are not known, being dependent on the previous cycle. The results of continuous operation might be obtained by figuring through cycle after cycle till a uniform condition is reached, in fact, after the first cycle practically uniform conditions will have been reached in most cases. The rigorously correct method given below is however just as simple.

In Fig. 1, the solid and dotted curves apply to the first cycle and a cycle of continuous operation respectively.

Then $Q\,P$ = initial motor torque in addition to friction torque, in a cycle of continuous action.

$Q'\,P'$ = final motor torque in addition to friction torque in the first cycle.

$Q'\,P'$ is known from the computations on the first cycle. $Q\,P$ bears a simple relation to it and is computed as follows.

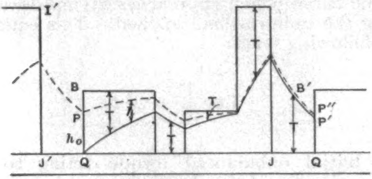


FIG. 1

It may be easily shown that the difference between the solid and dotted curves is represented by a continuous logarithmic curve whose equation is

$$\log \frac{h_0}{h} = A\,t$$

$$\text{Let } \frac{h_0}{h} \text{ for a whole cycle} = x$$

$$\text{Then } P'\,P'' = \frac{Q\,P}{x}$$

$$\text{now } Q\,P = Q'\,P''$$

Hence

$$Q\,P = Q'\,P' + P'\,P''$$

$$= Q'\,P' + \frac{Q\,P}{x}$$

$$\text{or, } Q\,P = Q'\,P'\left(\frac{x}{x-1}\right)$$

That is, to compute the correction to the initial motor torque, multiply the difference in motor torque at the beginning and end of the first cycle by the ratio $\frac{x}{x-1}$

where $\log x = A\, t_c$

t_c being the time for a whole cycle.

In cases where regulating devices are used to increase the slip when a given load is exceeded, we have to deal with sudden changes in the constant A. Referring to Fig. 2, when a certain load represented by the point P is reached, the regulating device acts. Due to its time element the introduction of resistance is delayed to the point P' after which a larger value A' of the constant prevails. The total motor torque is instantaneously reduced in the ratio $\frac{C\,D}{P'D} = \frac{A}{A'}$. The torque then increases along a second curve $C\,E$ with a much slower rise, due to the greater change in speed before a given change in torque takes place.

In computing the constant A (formula 55) the torques being ordinarily expressed in pound feet and $M\,K^2$ being expressed in pounds at one foot radius, it is advisable to introduce the factor G (= 32.16) directly in the formula.

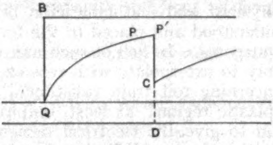


FIG. 2

In the very convenient diagram given by Mr. Gasche for computing A, M is expressed in the "gravitational" unit of mass which is equal to 32.16 pounds.

F. G. Gasche: I might give the assurance that the formulæ have been subjected to numerous applications and checked in many ways, such that the engineer may use them with some confidence.

Several years ago, the U. S. Steel Corporation inaugurated the construction of a large plant involving many features without precedent—at least in the magnitude of the several installations and the importance of the engineering problems.

It was proposed that, simultaneously, there should be complete motor driving of the rolling mills and that current should be furnished from a station involving a radical departure in the type of prime mover. There is nothing incompatible with these propositions provided the variations of frequency due to the action of the prime mover are negligibly small; but considerable variations introduce problems of great concern when the character of mill loads in the presence of a lowering voltage is understood. Should the prime movers be guilty of erratic control the safety and commercial efficiency of the entire equipment compels the use of flywheels and other safe guards. Many of these mill drives have been equipped with exceptionally large flywheels simply as a precautionary measure. This seeming extravagance has been attended by good fortune in the way of economies in the transmission of power and in the satisfactory service of the mill equipment.

Another complication arose from the ambition to surpass all precedents in the amount and rate of displacement of the metal in many of the roll passes, thus increasing the loads which would ordinarily be imposed on the driving motor. Preceding any other consideration in the power transmission problem, it became necessary to explore in a way that unknown region of the properties of materials which may be called the plastic state.

We have elaborately evolved mathematical theories of elasticity, and the statement of the laws applying to the region of " perfect elasticity ". Similarly, we have access to the theoretical hydro-mechanics, involving the assumption of "perfect mobility" or freedom from internal resistances. There remains to be investigated the " plastic region " promising to exact the best efforts of the physicist and mathematician before the subject is thoroughly understood and placed in the form most suitable for engineering purposes. In lieu of such assistance it becomes necessary not only to exterpolate with reference to our experimental data concerning roll train resistances, but also to investigate the "plastic region" at least, empirically, before we were in a postion to give the electrical designer the necessary load conditions within reasonable limits of error.

Possibly, a preliminary statement of the methods by which these roll-train resistances are estimated could have preceded the subject of the paper, but a subsequent statement of the case for the purpose of the Institute, if it is of sufficient interest will not suffer if suitable time is allotted to its preparation.

With regard to Mr. Dunn's observation concerning a statement in the paper, this is simply an interpretation of the formula (19) bearing in mind the value of the constant A containing MK^2 in the numerator. A zero value of MK' makes S equal to zero, or the motor does not assume the load due to the pass.

It is well within the possibilities that there is enough elasticity of the roll train connections in many cases to give an " approach " load condition as defined for Fig. 1. The allowance for such gradual assumption of the load would complicate the analyses beyond all requirements of practical applications unless the bar is actually a tapered ingot with little or no " draft " at the start of the pass. In this case, however, the statement to which Mr. Dunn refers does not apply when certain critical " torque-slip " relations of the motor have been established.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

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THE DESIGN OF THE ELECTRIC LOCOMOTIVE

BY N. W. STORER AND G. M. EATON

The features to be embodied in an ideal electric locomotive depend entirely on the point of view. Any electric locomotive, however, must contain certain essential features.

First. Mechanical parts of strength sufficient for the required service;

Second. Motors of capacity sufficient to develop the required power;

Third. A reliable transmission system between the motors and driving wheels;

Fourth. Weight on driving wheels sufficient for adhesion;

Fifth. A complete control system;

Sixth. Riding qualities enabling the locomotive to negotiate the rails without undue damage.

More or less closely associated with these essentials there is an endless variety of detail concerning which no two men will hold identical opinions.

The electric locomotive designer must act as a clearing house for the opinions and ideals of all the men associated with railroad electrification. To prepare himself for this position, he must view the locomotive through the eyes of men connected with every branch of the service.

Locomotive Ideals. The man who is responsible for hauling trains on schedule time sees a perspective that does not include first cost, weight, or mechanical or electrical efficiency, as those terms are generally understood. He sees in the electric locomotive only a means for keeping his trains moving, and on schedule time. His conception of efficiency is represented by the number of trips made on schedule time, divided by the total number of trips. He has had long, hard experience with steam locomotives, and is acquainted with their good and bad points. He accepts an electric locomotive only as a last resort, and then recommends the incorporation of as many as possible of the features of his successful steam locomotives. This on the face of it is a wise plan, but it should be remembered that a locomotive may be successful *because* of a given detail or it may be successful notwithstanding that particular feature. Again, a certain feature may be successful because of interrelation with other features, and a new design of locomotive must be carefully analyzed to see that an old and proven device will have the environment necessary for its best success. Too much emphasis cannot be laid on this point, as the differences in principle between steam and electric locomotives are not always easily recognizable. This point is well illustrated by fundamental differences in the application of cranks and connecting rods on steam and electric locomotives, which will be discussed in detail later.

The eyes of the motive power man see much the same features as those of the operating man, but his eyes magnify details of design in a greater degree. Both will wish to incorporate as many standard parts as can be used, and they will insist on the strength of all parts being ample to withstand every phase of the service such as bumping, speeding, overhauling, etc. They will be interested in the machine involving low maintenance charges, but in this respect they will not fully foresee the effect of the various mechanical features upon the electrical equipment, and they are liable to insist on the adoption of mechanical details, which of themselves have a low cost of maintenance, and yet at the same time will involve an excessive cost for the maintenance of the electrical equipment. Their ideal locomotive will operate safely at high speed, in either direction. It will be able to make up a reasonable amount of lost time, and will always be ready for service. It will not require long lay-overs, and will be in the shop the least possible time. They would like if possible a single type of locomotive which would perform any service that might be required of it, from making up and hauling a 2,500-ton freight train to making a high speed run with a "limited."

The amount of power consumed and the excessive weight involved in an interchangeable locomotive of this type are a matter of little importance to them, so long as the locomotive is strong enough to stand every phase of the service, and does not call forth protests from the maintenance-of-way department and bridge engineers. They know that such protests will certainly be forthcoming if damage to track and bridges is greater than that attendant upon the operation of the accepted types of steam locomotives.

Up to within a short time it has been the accepted idea that an electric locomotive would have riding qualities greatly superior to those of the steam locomotive, and that it would cause much less track destruction, due to the perfect balance and the absence of reciprocating parts. Recent experience has demonstrated that these features in themselves are not sufficient to produce a good tracking locomotive, and it is now generally recognized that the proportioning of an electric locomotive which will have ideal riding qualities is one of the most serious problems today confronting the designer.

The ideal locomotive of the general manager or president of the railroad is one that will meet as nearly as possible the ideals of his subordinates, and in addition will be a part of that system which will give the most reliable service, consistent with a reasonable cost of operation; or, in other words, will earn the largest dividends on the investment. The cost of the locomotive will appeal most strongly to him.

It is popularly supposed that the ideals of the electrical engineer concerning electric locomotives embrace only the electrical details of the locomotive, such as motor design, efficiency, temperature, and the control and collecting system, but this is a mistake at the present time, whatever it may have been in the past. It is necessary for him to have the broadest possible ideal. It is his duty in connection with steam locomotive designers to select that combination of details which will be the best compromise of the ideals of all railway people. It must be recognized that every complete design is a compromise, as much so in locomotives as in other machinery, and as long as the ideals of the different departments are conflicting it is certain that an ideal locomotive, from all points of view, will never be secured.

LOCOMOTIVE PROBLEMS

Transmission. At first sight it appears to be a very simple problem to transmit the power from rotating armatures to rotating wheels. This, however, is not the case, there being more or less serious objections and limitations to every type of transmission that has been proposed. Many of the types give excellent service when used in their proper places, but the fact remains that for high speeds and also for maximum powers, the problem of transmission is one of the most serious among the mechanical problems confronting the designer.

It will be helpful to classify the various types of transmission. Some of the objections and limitations of these types will be discussed later:

a. Gearless motor with armature pressed onto driving axle. "New York Central." Fig. 1.

b. Gearless motor with armature carried on a quill surrounding axle, and driving the wheels through flexible connections. "New Haven Passenger." Fig. 2

c. Geared motor with bearings directly on axle and with nose supported on spring borne parts of locomotive. "St. Clair Tunnel." Fig. 3.

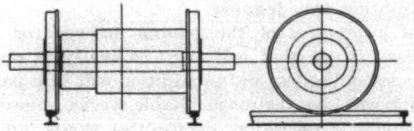


FIG. 1.

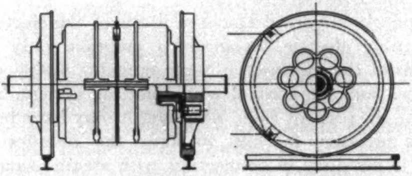


FIG. 2

d. Geared motor with bearings on a quill surrounding axle, and (1) nose supported on spring borne parts of machine (New Haven Car Fig. 4) and (2) motor, rigidly bolted to spring-borne parts of machine, the quill having sufficient clearance for axle movements. "Four-motor New Haven Freight." Fig. 5.

e. Motor mounted rigidly on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through cranks, connecting rods and countershaft on level with driver axles. "Pennsylvania" Fig. 6.

f. Motor mounting and transmission as in (*e*) but motor fitted with double bearings one part for centering motor crank axle and the other for centering the armature quill which surrounds and is flexibly connected to the motor crank axle. "Two-motor New Haven Freight." Fig. 7.

g. Motors mounted on spring borne parts, armature rotating at same rate as drivers, power transmitted to drivers through offset connecting rods and side rods. "Latest Simplon locomotives." Fig. 8.

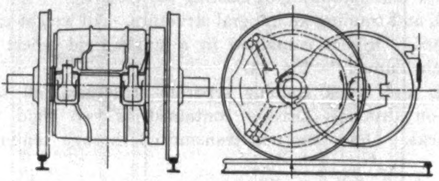


Fig. 3.

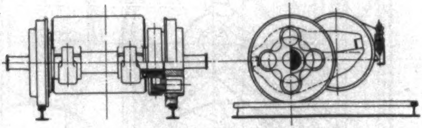


Fig 4

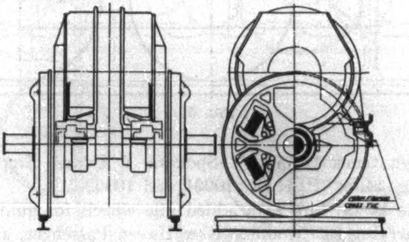


Fig. 5

h. Motors mounted on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through Scotch yokes and side rods. "Valtellina Locomotives." Fig. 9.

j. Motors mounted rigidly on spring-borne parts, power transmitted through gears to counter-shaft, thence to drivers through Scotch yokes and side rods. Fig. 10.

Further classification of electric locomotives on the basis of framing and wheel arrangement is also of assistance in gaining a clear understanding of existing locomotives.

a. Cab and framing an integral structure. All weight carried on drivers. Drivers contained in a single rigid wheel base. "St. Clair Tunnel." Fig. 11.

b. Cab and truck framing separate structures, all weight carried on drivers. Drivers contained in two rigid wheel base trucks. Draw bar pull transmitted through center pins or through truck frames. "Spokane & Inland Empire Ry. Co." Fig. 14. "P. R. R. 10001 and 10002."

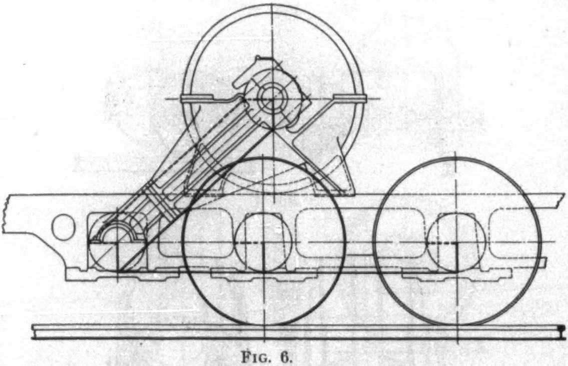


FIG. 6.

c. Same as (*b*) but with added idle wheels for guiding and weight carrying. "Modified New Haven Passenger, and New Haven Freight." Fig. 15.

d. Any of the foregoing forms permanently coupled in pairs or articulated. "Pennsylvania." Fig. 16.

e. Same as (*a*) but with added idle wheels for guiding and weight carrying. "Valtellina or New York Central." Fig. 13.

f. Cab and framing an integral structure. All weight carried on drivers. Driver wheel base partly rigid and partly flexible. "Simplon Tunnel." Fig. 12.

Service Requirements. It has been stated that from an operating standpoint it would be very desirable to have one locomotive which would be capable of handling at the desired speed any train from the heaviest freight to the fastest limited. While such a locomotive can be built, it will be at a prohibitive cost.

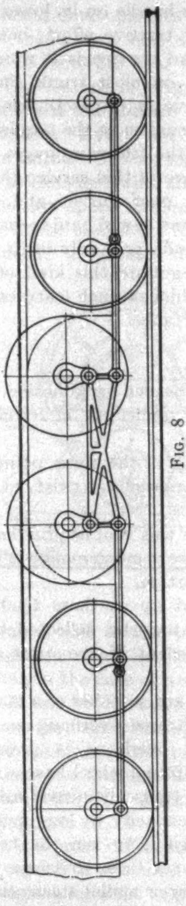


FIG. 8

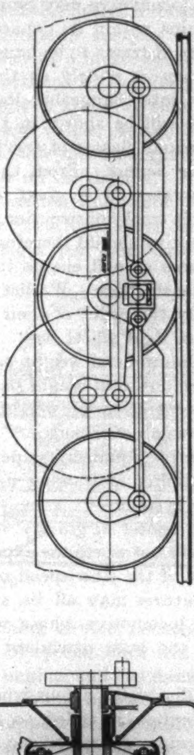


FIG. 9

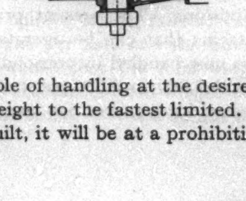


FIG. 7

It is commercially practicable to cover a considerable range of speed and weight of trailing load with one locomotive, and any passenger locomotive may be used to handle on its lower speeds freight trains within its capacity for tractive effort; but where the weights of trains to be handled and the speeds at which they operate vary as widely as they do on most trunk lines, an absolutely interchangeable locomotive is impracticable. This we believe will be shown in the discussion of the requirements for the various classes of service in the following pages.

Switching Service. From the nature of this service the locomotive operates to a great extent over curves and special work. This track construction is expensive and hard to maintain. The locomotive should therefore embody primarily in its design such features as will enable it to negotiate this kind of track with the least effort. We list the chief of such features in approximately the order of their importance.

(*a*) Short rigid wheel base.

(*b*) Minimum dead weight per axle.

(*c*) Minimum total weight per axle needed for adhesion.

(*d*) Concentration of weight near midlength of locomotive, and short cab overhang.

(*e*) Effective equalization perferably of the three point type.

(*f*) Flexibility of framing under longitudinal twist to assist equalizing system.

(*g*) High center of gravity. While this is of helpful tendency it is probably not worth the expenditure of much money or weight on account of the slow speed of operation.

These features may all be summed up as those tending to produce a locomotive whose wheels may be deflected by the rails with the least attendant movement of the mass of the locomotive.

Fig. 17 illustrates a four-wheel steam switcher of a standard type. Attention is called to the extreme overhang and consequent nosing characteristic. This overhang is practically inherent in a steam locomotive of minimum wheel base.

Slow Freight Service. Most of the transcontinental railroads are to day limited in their carrying capacity by long mountain grade divisions. The present practice is to run the heaviest freight trains that can be operated over these divisions. This service is now handled by consolidation or mallet steam engines, which haul 2,000 to 2,500 ton trains at 8 to 10 miles per hour, and electric locomotives are expected to handle the same or heavier trains at higher speeds to increase the capacity on the line.

The latest developments in locomotive design indicate that the type of locomotive best suited for such service, with speeds of 12 to 15 miles per hour is one having a motor geared to each axle. The feature of prime importance in the design of these locomotives is the absence of weight in excess of that necessary for adhesion. Every ton of excess weight in the locomotive means a ton less trailing load. A slow-speed freight locomotive should be designed with all weight on the drivers.

In the slow-speed service, the maximum allowable weight per axle should be used if the total weight of locomotive can be thereby reduced. A greater dead weight per axle can probably be tolerated than is wise in switching service, because being a road engine, a much less amount of special work will be negotiated than in the case of a switch engine, and the damage to the track will not be excessive at the normal operating speeds.

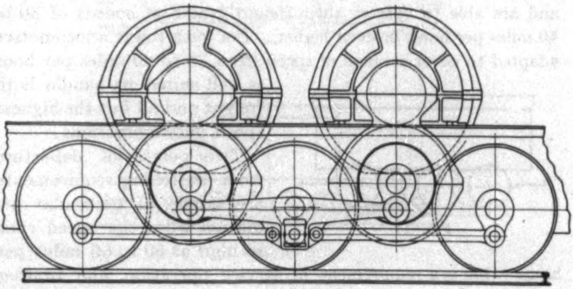


Fig. 10

If, however, complete spring support of the motors can be achieved without excess total weight, and this can usually be done, then the decrease in maintenance charges should much more than offset the increased first cost attendant upon such spring support.

There is a great difference of opinion among railway engineers both in regard to the total weight per axle and the amount of dead weight allowable. Some would keep the total weight per axle below 40,000 lb. and the amount of dead weight equal to that of wheels, axles and journal boxes. Others do not hesitate to put 60,000 lb. on a single pair of wheels with a dead load of 15,000 to 18,000 lb.

The intention here is not to attempt placing strict limits on axle loads, but to call attention to general tendencies, as each actual installation must be settled upon its own merits, or in accordance with the practice on the particular line involved.

The wheel base of the slow-freight engine should be as flexible as possible so as to curve easily and prevent flange wear, and should take switches and turnouts without undue stress on the track. No idle leading or trailing truck axles will be necessary. The remarks on high center of gravity, equalization, concentration of weight at midlength of engine and flexible framing apply almost equally on switching and slow freight services.

Fast Freight Service. Some trunk lines have no heavy grades, and are able to operate their freight trains at speeds of 30 to 40 miles per hour, or even higher. For such roads a locomotive adapted to cover a range of speed from 30 to 60 miles per hour is well suited to handle both freight and all but the highest speed passenger trains.

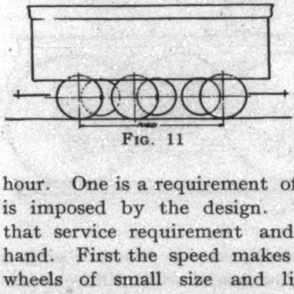


FIG. 11

Two points of departure from switching requirements are worthy of particular attention when the speed runs as high as 50 to 60 miles per hour. One is a requirement of service operation, and another is imposed by the design. These points are interesting in that service requirement and design limitation go hand in hand. First the speed makes it advisable to provide leading wheels of small size and light dead weight to assist in guiding and more particularly to iron the rails down gently to an actual bearing surface on the road bed and thus avoid the knock attendant on hammering the free rail down with the heavy drive wheel. Second, as the speed increases, either the tractive effort decreases with less weight required on drivers or the horse power demanded increases with attendant weight increase and the added wheels are necessary to avoid overloading the drive wheels.

High Speed Passenger Service. The most important requisite of a locomotive designed to operate at 60 miles per hour and over is its ability to run at the highest speeds possible without injury to the track. All the track disturbances mentioned above, except in curves and special work, have been primarily in a vertical plane. When we consider speeds of 50 to 60 miles per hour, however, we are closely approaching the range where even on tangent track serious lateral disturbance is liable to occur. Extensive speed tests have shown that almost any kind of a machine will stay on the track at 40 miles per hour, without serious damage to tangent track. As the speeds increase above this figure, however, the bad riding qualities rapidly appear. The particular features following apply with more and more importance as the speed increases so that we are led naturally to a consideration of the higher speed machines, bearing in mind again that no sharp dividing line exists and individual conditions must govern all concrete cases.

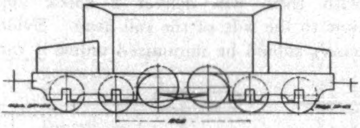


FIG. 12

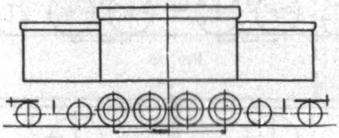


FIG. 13

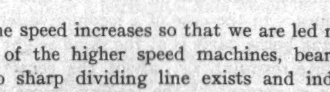


FIG. 14

There are certain features that tend to reduce the intensity of the lateral forces on the track. First of these, and a source of much recent comment, is "high center of gravity." The acceptance of this as a cardinal principle of successful high speeding, however, is not universal. The theory on which the belief in the value of a high center of gravity is based is that the higher the mass of the locomotive is placed above the axles, the less will be its restraining influence against lateral motion on the part of the wheels. The mass of the locomotive may take the general direction of the track while the wheels follow all the little irregularities in its surface and alignment.

Assume for instance, that a locomotive is running at high speed on tangent track and that some rail defect imposes sudden transverse movement upon the wheels. Under these conditions the mass of the wheels and axle and any other masses rigidly associated with them will deliver a shock approximating a hammer blow to the side of the rail head. Evidently therefore these masses should be minimized unless it can be shown that their increase does not involve serious injury to the track and consequent danger in operation.

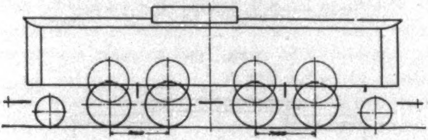


FIG. 15

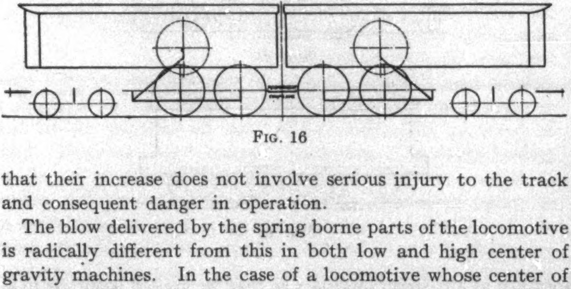


FIG. 16

The blow delivered by the spring borne parts of the locomotive is radically different from this in both low and high center of gravity machines. In the case of a locomotive whose center of gravity of spring borne parts is at the same height as the center of the transverse restraint, *i.e.*, about the center of the axle the transverse movement of the leading driver would impose a rotation of spring borne parts about a vertical axis. Fig. 19. The lateral force to impose such a movement would be very great, due to the great moment of inertia about this axis. In the case of a locomotive whose center of gravity is high above the center of transverse restraint the movement imposed upon the spring-borne masses by transverse movement of the leading driver is a composite of two rotations, viz., about a vertical axis and about a horizontal axis parallel to the rails. Fig. 20. As the moment of inertia about the latter axis is much less than that about the former it is evident that the lateral forces involved in the high center of gravity machine will be less. The forces opposing rotation about horizontal axis are provided by the semi-elliptic riding springs, which will transmit their resultants ultimately to the running face of the rail and will not aggravate flange pressures. Were it not for the dampening effect of the friction of the semi-elliptic springs and the detail friction of the machine, this rotation about a horizontal axis would be a simple harmonic vibration. The period and amplitude of this vibration would be functions of the characteristics of the semi-elliptic springs and of the polar moment of inertia of the masses moved.

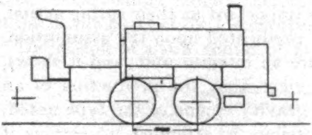


FIG. 17

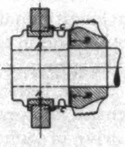


FIG 18

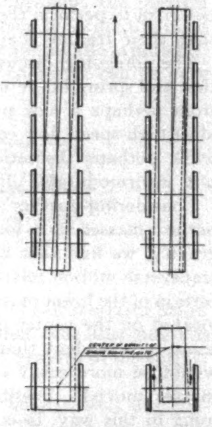


FIG. 19 FIG. 20

Suppose for example that with the low center of gravity locomotive first considered, some combination of lateral springs were applied which would impose on the spring-borne weights a vibration about the vertical axis of period and amplitude and dampening action identical with that occurring on the high center of gravity machine. There being no rotation about the horizontal axis, the forces required to control the vibration would be greater than with the high center of gravity machine, because of greater moment of inertia about the vertical axis; and further, the transverse rail stresses would be greater because the reactions of the controlling forces are transverse.

We can formulate an idea of the springs necessary for such transverse restraint by comparing them with the semi-elliptic riding springs which perform the dual function of supporting weight and resisting rotation about the horizontal axis. Probably transverse springs as heavy and with as great amplitude of motion as these semi-elliptic riding springs would be none too powerful to perform the required service, and it should be noted that their friction is almost as important as their spring action.

The foregoing discussion is predicated upon the assumption, that the spring borne masses are an integral unit; and it shows, from perhaps a new point of view, that the production of an ideal high-speed, low center of gravity engine of the type noted, while perhaps theoretically possible, is attended by serious if not insurmountable difficulties.

Considering further this horizontal rotation of the spring-borne masses of a locomotive with medium height of center gravity, we find that there is a zone that is neutral as regards transverse motion relative to the track. If in such a locomotive certain of the lower masses were hung from longitudinal trunnions located on the center line of the locomotive and in this neutral zone, it is evident that the rotation of the spring-borne masses would be more easily accomplished due to the lessening of the masses moved. Possibly gearless concentric motors could be hung in this way, in connection with a drive of sufficient flexibility to allow free wheel play.

This is not a combination that could be recommended solely because of good riding qualities. It is, however, entirely possible for such a machine to have sufficient attendant simplicity to make it a better compromise than an engine where simplicity and mechanical efficiency are directly sacrificed to secure high center of gravity.

It may be mentioned that the New Haven locomotives have a motor mounting that approximates this condition. There is not as great amplitude of springs to allow unrestrained wheel play either vertically or laterally as might be desired, but there is enough to cushion all blows that the track receives from the mass of the motors, and the reports of track maintenance since the addition of the leading wheels eliminated the nosing tendency, are very gratifying.

Almost equally advantageous with the high center of gravity is the concentration of the mass of the locomotive about this center of gravity, both vertically and longitudinally. It is conceivable that if the mass of the locomotive could be so concentrated longitudinally about the center of gravity as to decrease the radius of gyration about the vertical axis to a value well within the rigid wheel base, there would be no more serious lateral disturbance on the track with a low center of gravity machine than with one having higher center of gravity but with a much longer radius of gyration about the vertical axis. Every effort should, therefore, be made to locate the mass of the heavy parts of the locomotive as near the middle as possible.

The action of a low center of gravity locomotive can be very materially improved by locating the point of side restraint below the level of the driving axles. Every inch that this point is lowered is equivalent to raising the center of gravity of the spring-borne parts by an equal amount.

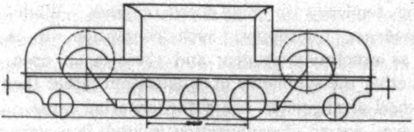


FIG. 21

Wheel Sizes. On a steam locomotive, large wheels are considered essential for high speed service. The primary reasons are to minimize the wear and tear on parts subjected to reciprocating stresses, to maintain the piston speed at a safe figure, and to keep down the blow on the track due to the incorrect counterbalance. An advantage of large wheels in any high speed engine lies in the attendant low surface speed of the journal, and again in the long time elapsing between tire turnings. There is also less distress of metal in both tire and rail, due to the greater area of contact with the large wheel. On the question of the advantage of large wheels for road engines, there is probably a greater unanimity of opinion among railway men than on any other detail of the equipment.

Equalization. The most successful high-speed steam locomotives of to-day are designed with a three-point equalization, having one point ahead and two trailing. This is apparently a very desirable arrangement for any locomotive, and the electric locomotive designer is at once confronted with a new problem in adapting it to a locomotive which must be designed to operate equally well in either direction. The only means by which the actual three-point equalization can be secured on such an engine is to devise some means for shifting the equalization when the engine is reversed. It is possible to arrange air cylinders interlocked to the reverse lever, which will automatically alter the equalization system, so that a single point of equalization will always lead and two-points will always trail. This should, however, be reserved for a last resort, as it does not seem wise to accept such weight and complication unless it proves essential.

A symmetrical arrangement of wheels on the two ends of the locomotive has been criticised by some as lending itself to a nosing tendency in high-speed engines. While there is some evidence to support such contention, it is not regarded as absolutely proven, and there is an open question as to whether the symmetry of equalization rather than symmetry of wheel arrangement is not the irritating cause.

Whatever system of equalization is used, it is very desirable that the springs on an electric locomotive should be very flexible. This in itself will tend to equalize the loads on the drivers without the complete three-point equalization system. It is contended by some of the best engineers that a four-point equalization system with flexible springs is better than the three-point equalization system.

Interchangeable Locomotives. If the accuracy of the foregoing outline of features for various services is accepted, the impracticability of performing all classes of service economically with a single machine, is at once made apparent. The engine for the heavy high speed passenger train will require motors of large capacity. This capacity, however, can be utilized only at the high speeds with a corresponding low tractive effort. The electric locomotive is not so well suited for interchangeable service as the steam locomotive because of the fact that its continuous tractive effort is practically constant regardless of the speed at which it is operated. A steam locomotive, on the other hand, can develop its maximum horse power at almost any speed, and its continuous tractive effort may be anything from its maximum, which is developed at starting, down to that necessary to give its maximum horse power at its maximum speed. An electric locomotive designed to develop its continuous capacity at 60 miles per hour, if operated in freight service at 30 miles per hour will be developing only one-half of its capacity. On account of the necessity of having the best riding qualities at high speed, the locomotive will be very much heavier than one designed especially for freight service having the same continuous tractive effort. The cost also will be much greater. It may be contended that where gearless motors are used, it is simply a matter of winding the motor to develop a given tractive effort at its maximum speed, and it will then be suitable for any service requiring this tractive effort at lower speeds. This is true, but for mechanical reasons the converse is not true; namely, that a freight locomotive can be operated in passenger service by winding the motors for a higher speed. An economical mechanical design for a locomotive, which is thoroughly satisfactory for freight service, will not be at all suitable for the high speed passenger service. Steam locomotives have been used interchangeably to some extent in railway service, but in general this has been found impracticable.

Transmission from Motor to Wheel. At the beginning of the paper it was stated that the transmission of power from the motor to the driving wheels is one of the most serious problems confronting the designer. It is closely allied with the type of framing, wheel base, and location of center of gravity of the locomotive. While many types of transmission are in successful operation, none is above criticism from some point of view.

Gearless Concentric Motors. It is well known that gearless motors in which the armature is carried dead on the axle while having the simplest transmission of all are destructive to roadbed when operated at high speeds. The mounting of the motor on a quill driving the wheels through springs is also objectionable from some standpoints, but it is open to less objection from the fact that its weight is all spring-supported against both vertical and lateral shocks.

There is a definite, though somewhat restricted, field where the gearless concentric motor is most successful. High service speed is essential to allow a rate of revolution sufficient to secure an economical power output per unit weight of motor. The gearless concentric motor for slow-speed operation cannot compete with the geared motor, as the weight and cost will be prohibitive. The power demanded per axle must not be so great as to result in wheel overloads.

TRANSMISSION THROUGH GEARS

Gears are very unpopular in many quarters, and have unquestionably some disadvantages. However, there is probably no part of the standard street car motor equipment which has given less trouble than the gears and pinions. There have been many cases of broken gears and of gears that have had an unduly short life, but all of these cases could be traced to a cause or causes which are now well understood, and can easily be avoided.

We feel perfectly safe in saying that, in the present state of the art, gears can be designed which will perform satisfactorily in any class of railway service. The improvements which have been made in the quality of gears and pinions by the use of high-grade materials having greater strength, higher elastic limits, and improved wearing qualities, are such that there should be no hesitancy on the part of the locomotive designer in recommending gears for service where a reduction from the armature speed is desirable, as in low-speed locomotives.

Gears for very slow-speed work may be pressed on the driving axle as in ordinary street car work. Where the motors are of large capacity, it will be necessary to use twin gears, as in the case of the locomotives for the Cascade Tunnel, and the high-speed freight locomotive No. 071 for the New York, New Haven & Hartford, R. R. The former has the gears pressed directly on the axle, but in the latter, the gears are mounted on quills. This latter design is much to be preferred, and is in fact necessary where the locomotives are to be operated at speeds much above 30 miles per hour. The use of the quill, of course, involves a further connection between the quill and the driving wheels. This is accomplished in the case of the New Haven locomotive by long helical springs, one end of which is clamped to a projection from the quill and the other to the spoke of the driving wheels. These springs have such a large amplitude of motion that the axle is almost entirely unrestrained by the motor which is mounted rigidly on the truck framing. On this locomotive the gears are also provided with a spring connection between the rim of the gear and the center, which removes practically all of the shock due to high pitch line speed, and at the same time divides the load equally between the two gears on the quill.

A further advantage of gearing the motor to a quill having large clearance around the axle is that it enables the motor to be mounted rigidly on the truck, and directly above the axle, thus permitting the greatest economy of space by bringing the driving axles close together. It also raises the center of gravity of the spring-borne parts and brings the motor well above the dust and dirt of the roadbed. And as the motor projects through the floor into the cab, the commutator, brushes and oil boxes are rendered accessible at all times. It also facilitates the use of forced ventilation which greatly increases the capacity of motors of the enclosed type. The limitations of this type of transmission are not yet well defined, as it has been in use but a short time, but the performance thus far has been so satisfactory as to give promise of its success in a wide range of application. It is believed that on account of the extreme flexibility of the drive that the pitch line speed may be raised to a much higher value than has ever before been deemed possible. The flexibility effectually prevents the extreme shocks which are ordinarily received by the gear teeth of a high speed locomotive when the gear is pressed directly on the axle.

The use of gearing which permits the armature to run at a higher speed of rotation than the driving axle, places a limit on the speed of the locomotive which from the point of view of the operating man may be undesirable. It is necessary in designing such a locomotive to consider the maximum speed at which the locomotive is to be operated and leave a margin above this figure before the safe limit of the armature speed is reached. The service conditions will determine the maximum locomotive speed and also the speed at which the motors should develop their continuous rating horse power. These two locomotive speeds and the limiting peripheral speed of the armature, together with the desired horse power output form the mechanical basis for the motor design. For economical designs it is not advisable to allow a maximum armature speed of more than 2 or 2.5 times the continuous rating speed. If a greater ratio than this is required, the armature speed must be reduced. The weight and cost of motor for a given continuous capacity will increase directly with this ratio.

Some of the other limits in a geared motor design are the pressure per inch width of gear face at the continuous rating, and the directly associated limit of the available distance between wheels, which must be divided between the gears and the motor. The available gear reduction is limited, on the one hand, by the diametral pitch necessary to secure a tooth with sufficient strength or life, together with the minimum number of teeth in the pinion consistent with low maintenance; and on the other hand, by the maximum number of teeth in the gear that can be applied with a given diameter of driving wheel with sufficient rail clearance.

With theoretically perfect gears a very high pitch line speed should be operative. In regular interurban mounting of motors, heavy strains are imposed on gear teeth in high speed operation by sudden vertical displacement of wheels due to track irregularities, with attendant acceleration or retardation of armature. In such applications a maximum pitch-line speed of 3,500 to 4,000 ft. per minute is operative. With complete spring support of motor and flexible connection to wheels, or with flexible gears, it is evident that a higher speed will be permissible. There are insufficient data at hand to approximate the limit under these conditions.

The above statements are all based on the use of spur gears and it is confidently expected that even better results can be obtained by the use of helical gears which are now coming into use. The success of this type of gear which is used for the Melville-McAlpin steam turbine drive indicates a sphere of usefulness for gears which has scarcely been touched.

While it is too early in the use of gears for large locomotives, to make an absolute statement of fact in regard to the allowable pressures, experience thus far indicates a pressure of 1,000 lb. per inch width of gear face as a perfectly practicable value for continuous rating of large gears. With special steel pinions and high grade gears it is probably safe to exceed this figure. It is well known that for short hauls pressures far above 1,000 lb. per inch are now in daily successful operation. In the locomotives for the St. Clair Tunnel, for instance, the pressure is carried on a single gear having a 6-in. width of face. The normal loads at which the locomotive operates on the up-grade give a pressure of from 1,500 to 2,000 lb. per inch width of face on the gears. With this pressure the pinions have a life of 40,000 to 50,000 miles, and none of the gears has yet worn out, although the locomotives have been in continuous operation for over two years. With twin gears there is a possibility of further increase in unit pressure as the absence of relative skewing of pinion and gear shafts produces a better application of the tooth load.

Probably the greatest limitation to the use of motors geared to the axles or to quills surrounding the axles is the restricted space between the wheels. As the output of the motor increases the width of the gear face must increase also, and this extra gear space must be deducted from the space ordinarily occupied by the motor. This results in motors having a larger diameter than would ordinarily be designed. In spite of this limitation, however, it is probable that geared motors as large as 500 h.p. continuous rating will be used. This is about as great an output as can be utilized on a single axle.

TRANSMISSION BY SIDE RODS

A desire to secure the good riding qualities of the high-speed steam locomotive, and at the same time to avoid the difficulties and limitations imposed by mounting the motor concentric with the axle, has lead to the adoption of side rods for transmitting the power from the motor to the wheels. There is a very strong tendency in this direction both in Europe and in this country. The general form universally adopted except for the three phase locomotives in Italy and Switzerland, which will be discussed separately, is that of the now familiar Pennsylvania locomotive which is illustrated by Fig. 6. The motor is mounted on top of the locomotive framing, and the armature shaft connected by quartered cranks to a jack-shaft located in the same plane as the driving axles. The power is transmitted from the jack-shaft to the wheels by other parallel rods.

This type possesses some very distinct advantages. It permits the use of a single powerful motor to drive two axles. The motor is mounted in the cab instead of under it so that all parts are readily accessible and are thoroughly protected from the dust, dirt and water from the road bed. The location of the heavy motor so high in the cab raises the center of gravity of the locomotive to a height corresponding to that of high-speed steam locomotives. The side rods form a transmission system that is familiar to all steam locomotive operators. It apparently has all the good points of the steam locomotive rods and is, in addition, susceptible of perfect mechanical balance and gives a uniform tractive effort.

There are, however, certain fundamental differences between the performances of side rods on steam and electric locomotives.

1. The steam locomotive transforms the heat energy of the steam into mechanical work by means of a reciprocating engine. Connecting rods and cranks are therefore essential

features. The electric locomotive on the other hand develops its power by rotation and no single type of transmission can be listed as indispensable.

2. In case of a steam locomotive there are at least two independent sources of mechanical forces, viz., the cylinders. Each piston constitutes a "free end" of the transmission system. The distance from the center of cylinder to the center of main driver axle is not a hard and fast value, as a slight variation means only a change of crosshead overrun and of cylinder clearances. In an electric locomotive where there is a single motor, crank and rod connected to a countershaft, there are no "free ends" to the system. For this reason great accuracy of tram and parallelism of motor shaft and countershaft are essential, any error being accompanied by serious stresses in the transmission with associated low mechanical efficiency and high maintenance charge, especially for bearing brasses.

3. In the steam engine the stresses on the transmission system at any point in the cycle can be very closely approximated by means of indicator cards taken from the cylinder, together with centrifugal stresses. In other words, each side of the engine can be considered separately. With the electric locomotive on the other hand, there is but one source of mechanical force; viz., the motor which exerts a constant turning moment or torque throughout the entire revolution. This constant torque must be transmitted to the driving axle without modification except for the losses in bearings. At certain points in the cycle all the torque of the motors is transmitted through one crank; at certain other points it is transmitted through the opposite crank. At intermediate points it may or may not be transmitted through a single crank, as the interchange of work is different in different machines, being a composite function of journal and pin clearances together with bending and torsional deflections of all elements of the transmission and framing. It is therefore not possible to analyze the forces on one side of the locomotive independently of the other side.

4. In the steam locomotive the main rod connects the cross head to the drive wheels. In the electric, all the driving effort is transmitted through four running pins in series before any useful work is performed. This results in considerable loss of mechanical efficiency. It may be noted that the use of knuckle pins would avoid one or possibly two of the running pins mentioned but thus far no railway operator has been found in this country who

is willing to accept knuckle pins in an electric locomotive. Knuckle pins have caused so much trouble from breakage that they will have to be modified considerably before they will be acceptable. The trouble seems to lie in the twisting of the rods due to uneven track.

The side rod type of locomotive is at a disadvantage when compared with the high-speed geared type described, because of the fact that the mechanical parts of the locomotive and also the motor frames must necessarily be much heavier to withstand the reciprocating stresses imposed on them. They will also require much more careful work in assembling and will therefore be more expensive. On the other hand, it would seem that after the side-rod locomotive is once completed, the mechanical parts should be very cheap to maintain. The results of the operation of the Pennsylvania locomotives will be awaited with great interest.

SCOTCH YOKE SIDE ROD TYPE

The type of drive which has been used to the greatest extent with the three-phase locomotives in Italy is that illustrated in Fig. 9, utilizing the so-called "Scotch Yoke" for connecting the motors with the driving wheels. This has been in use for several years and has apparently given excellent results. In these machines much of the criticism attendant upon connecting rod applications has been obviated. The motors, being flexibly attached to the spring-borne parts, are not subject to severe cranking strains and can therefore be made light mechanically. The motor shafts, it is true, should line and tram accurately but they are so located that this can be done with minimum difficulty. The mechanical parts also can be made considerably lighter because of the fact that there is no jack-shaft required, and the cranking strains are taken directly on the armature shafts which are supported in bearings in the side frames. The design, however, sacrifices high center of gravity, and some alternate plan for securing easy riding qualities must be adopted. One which has been suggested utilizes a plan somewhat in line with that suggested for the gearless concentric motors; namely having springs between the motor and side frames for cushioning lateral shocks. The mechanical efficiency of this type should be higher than that of the rod-connected design, because of the fact that the power is not transmitted through so many running pins. It has the objectionable feature of a sliding connection between the driving yoke and the pin on the middle driving wheel, but this apparently causes no trouble whatever. In fact, the locomotives as observed on the Valtellina Railway operate smoothly, and apparently with small friction loss. This may be ascribed in part to the fact that all bearings are kept flooded with oil. The use of knuckle pins for transmitting power from the "Scotch Yoke" to the outer driving wheels is made perfectly safe by the use of spherical pins or spherical bearings.

This type of drive will give probably a lighter locomotive than is possible with any other drive having motors operating at the same speed as the driving axles. It has thus far not met with favor in this country, but its merits will undoubtedly bring it into use for moderate speed work where gearless motors are desired.

COMBINATION GEAR AND CONNECTING ROD DRIVE.

Where slower speeds are desired than can be secured by the use of motors operating at the same speed as the axles it is sometimes more economical to use two motors geared to jackshafts and connected to the drivers by means of the "Scotch Yoke" in the same way as just described. Fig. 10. This scheme has some advantageous features which are not at first apparent. It permits the use of large motors and gives much greater space for them than can be secured between the drive wheels where the motors are geared either to the axles or to quills surrounding the axles. The motor is mounted so that its center of gravity is high, and as it extends through the floor into the cab, the bearings and brushes are easily accessible. In this respect the motor has all of the advantages possessed by the rod-connected motor. Gears can be located outside of the driving wheel so that they can be replaced without dismantling the locomotive any further than required by the removal of the side rods. Locomotives involving this priciple have been built in Europe, and a large one is now under construction for the Midi Railway in France. As stated before, it is especially fitted for work where it is desirable to reduce the number of motors to a minimum and at the same time operate at slow speeds with heavy tractive efforts.

This locomotive, however, is subject to such criticism as is involved in synchronous revolution of many parts with a consequent loss in efficiency and with possible inertia complications. In this respect it is practically on a par with all rod-connected locomotives.

ROD-CONNECTED LOCOMOTIVE WITH RADIAL AXLE

A description of the principal types of transmission would scarcely be complete without mention of the three-phase locomotives now in use in the Simplon Tunnel. These locomotives have been described in the technical press. The chief point of interest lies in the location of the motors, the connection to the drivers, and in the radial driving wheels at the ends of the locomotive. The motors are located as close together at the middle of the locomotive as possible, and their crank pins are connected together by a frame. From pins on this frame on a line with the center of the axles, rods are carried to the nearest driving wheels, and thence other rods connected to the axles of the outer drivers, there being four pairs of driving wheels. It is, of course, essential where side rods are used that all axles should remain substantially parallel, and in order to secure the radial motion of the wheels at the ends of the locomotives, it is necessary to mount the wheels on quills which surround the axles and connect them together only at the middle point by a kind of universal joint. By these means the wheels are able to move in a radial direction, while the axles which drive them are kept parallel to the inside driving axles. This seems to be operating very satisfactorily, and with some modifications will probably meet other conditions where all the weight is carried on the drivers, and a rigid frame locomotive with flexible wheel base is required.

CONCLUSION

The foregoing survey is incomplete, as the possible combinations of locomotive framing, motors, and transmission between motors and drivers are almost limitless, and it would be impossible in a paper of reasonable length to discuss even those that are well-known. The aim has been to present the problem as viewed by the authors, and to discuss a few of the fundamental principles on which the design of the locomotive should be based.

The problem is in a word: To design a locomotive incorporating all essential features, and as many non-essential but desirable features as possible, and for a price that will make electrification attractive to railway officials.

DISCUSSION ON "THE DESIGN OF THE ELECTRIC LOCOMOTIVE". JEFFERSON, N. H., JULY 1, 1910.

Wm. McClellan: I should like to emphasize the absolute necessity of designing electric locomotives with reference to track conditions.

As speeds increase and loads get heavier, maintenance of track is difficult in any case. It is especially so, however, when trains of a great variety of speeds pass over the same track. Roadway men know how difficult it is to fix proper elevation of rail, surface and align the rail, and bed the ties so that the result will be equally good for low-speed freight trains and for high-speed passenger trains.

In regard to the question of interchangeability, there is another feature which is of great importance. In freight service, we cannot dispatch trains and adhere closely to the schedule with the same degree of accuracy that we can in passenger service. We can design a locomotive for handling a certain kind of passenger service and it is quite likely that the locomotive will not often be used under very different conditions. On the other hand we may design a locomotive for a certain kind of freight service, and instead, for example, of going over the road with few stops at a good speed, traffic conditions may compel it to start and stop with great frequency, or run at an extremely low speed for the bulk of the time. To put it differently, the freight locomotive may be designed for through service, but may be compelled through the exigencies of conditions to do the equivalent of switching service. This does not apply to the electrification done so far which has been chiefly on tunnels and grades.

A. F. Batchelder: There are a few points to which I would call special attention and about which I cannot fully agree with the paper.

As to the order of importance of the different points of design, I cannot agree that the dead weight per axle is necessarily second. A great many differently designed locomotives have been built and operated. So far as my experience goes, I have not seen as yet, neither have I been able to find anybody that has seen, any design where the dead weight has had any detrimental effect on the track as long as it is limited to the weight of the motors, the journal boxes, spring saddles, and with the rotating parts balanced and the trucks properly equalized.

There are electric locomotives in regular operation that have dead weight per axle as high as 17,000 lb., and so far as I can learn, there is no indication that this dead weight has any bad effect on the road bed or track.

Of course it is well understood that on steam locomotives where the wheels are not well balanced and the locomotive running at high speeds, the unbalanced weight has a bad effect on the rails and road bed.

Relative to the height of the center of gravity being important, I believe a high center of gravity will assist in making an easy guiding locomotive, providing the spring supported portion is carried on journals placed between the wheels, making the spring centers approximately 42 in. apart, as is the general practice on steam locomotives; but with electric locomotives with outside journal boxes where the spring centers are placed approximately 80 in. apart, a high center of gravity say from 60 to 75 in. is but very little assistance to making the locomotive guide easily.

The feature desirable to obtain is the rolling effect in entering curves, and it will be seen that the rolling effect will be much less with a high center of gravity locomotive where the spring centers are 80 in. apart than it would be if the spring centers were only 42 in. apart. It will be seen that in order to obtain the same effect where the spring centers are 80 in. apart it is necessary to have the height of center of gravity above the point of thrust nearly twice as great as with spring centers 42 in. apart.

The paper also speaks of the different opinions of engineers and their choice as to the weight per axle. It has been my experience that it is not the opinion of the engineers, but the physical conditions such as the weight of rail, and strength of bridges and road bed, that determine the weight per axle allowed, and the railway engineer is in position to know these, and insist upon designing the locomotives to suit the conditions.

Another point that the paper brings out very nicely is the necessity of concentrating the mass of the locomotive as near the center as possible. I might add that it is also desirable to make the guiding wheels as far forward of this weight as possible, as it is well understood that if we have something to guide, the longer the handle the easier it is to manage.

I might also mention that it is the spring-borne portion of the locomotive that is the most difficult to manage. It is this portion that can set up oscillations and build up a movement that is difficult to stop without doing damage to the track by the guiding wheels. If the greater portion of the weight of the spring-borne part is concentrated near the center or well back from the guiding wheels and with a damper to prevent its building up oscillation, it is perfectly practicable to guide a very heavy locomotive without damage to the track.

Every locomotive truck that runs on rails is bound to oscillate from one side to the other, on some portion of the railroad, and it is practically impossible to make a locomotive run without doing this. Therefore, it is necessary for us to accept this oscillation as being inherent, and for high-speed locomotives, we must design so that this oscillation will do no damage.

It may be interesting to examine the design of the locomotive shown in the accompanying illustration which I believe embodies most of the desirable features discussed and which we have worked out to meet the requirements of heavy trunk line service; it has a tractive effort of nearly 30,000 lb., continuously, and a maximum tractive effort for short intervals of time of 80,000 lb.

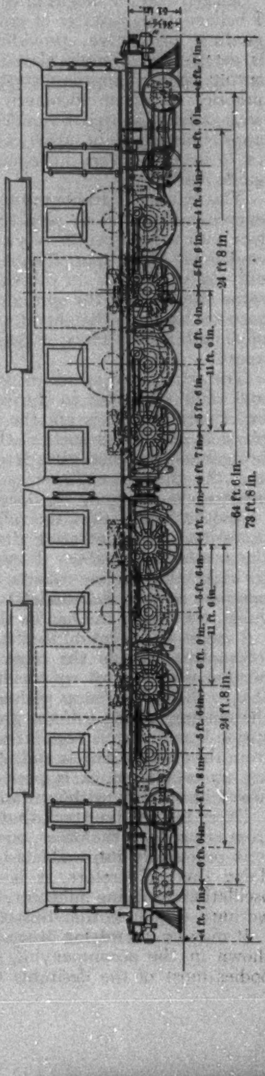
It will be noted that it has a reasonably high center of gravity, narrow distances between springs, the weight of the spring-borne portion well back from the guiding wheels, motor flexibly supported, and each driving axle is driven through quartering cranks and side rods from a jack shaft which is driven by the motor through spur gearing.

We have looked into this design very carefully and find it possible to build it with motors of sufficient capacity for the heavy trunk line service on mountain divisions and keep the total weight within reasonable limits.

In general the locomotive is made up of two American type engines coupled back to back having two driving axles and a two axle leading truck on each section.

It has been well proven that the American type engines operate very satisfactorily at all speeds on our American railroads and for this reason, I believe that this type of electric locomotive will operate the same under the same conditions.

Frank J. Sprague: I cannot express my belief as to the best type of electric locomotives, for I am a member of the Electrical Commission of a prominent railroad company which will soon be engaged in the task of dissecting proposals which have been accumulating for the past eight or nine months, from manufac-



turing companies, involving quite a variety of locomotive designs as well as methods of motor operation. It would, therefore, be improper for me at the present to express any preference for a particular design, even if I had any. As a matter of fact, I am of an open mind.

We can all agree with the authors in the general statement of the requirements of an electric locomotive, which might more tersely be stated to the effect that we want to get all that we can in capacity and good tracking characteristics for the least money. That I think is the argument which will appeal in behalf of electric traction to railroad officers and engineers. Not only must we seek all that is possible in the matter of capacity and good riding qualities, but also incorporate in the locomotive all that is practicable which has been found to be good in the steam locomotive, but which is not necessarily individual to, or especially characteristic of steam operation, and also all that is good so far as possible in electric operation. Now, how? I suppose there are few engineers of maintenance who do not at times think the superintendent of motive power ought to scrap most of his engines, and likewise it is a good natured and patient superintendent of motive power who does not occasionally condemn the track engineer for the condition of his track. Perhaps that is stating the facts a bit strongly, but it illustrates the feeling which exists oftentimes between two great operating departments of our railroads which should coöperate, because after all the locomotive and the track are married, and you cannot divorce them. Each affects the other, and neither has the right of way over the other; both are vital to the operation of the railroad.

The authors describe various methods of motor mounting and their effect upon the construction of the locomotives. I find it more convenient to consider locomotives, at first, irrespective of their motor mountings, and as divided broadly into three classes: locomotives with fixed wheel bases, either with or without a leading truck, the truck having either one or two axles; locomotives with bogie trucks, symmetrical or otherwise, and either linked together or independent; and articulated locomotives, that is, made up of two sections each having drivers forming a fixed wheel base, and with a bogie truck, the two parts being hitched back to back. There are many modifications of these types. Each of these forms can have a variety of motor mountings. A typical example of the first are the locomotives of the New York Central & Hudson River Railroad; of the second, the locomotives running on the New York, New Haven & Hartford Railroad, on the Great Northern, and in the Detroit Tunnel; and of the third, the locomotives which are being installed on the Pennsylvania railroad. Motors can be geared, according to my original practice, and there are some scores of thousands running that way, many of them at almost the maximum speeds that are attained by any steam locomotive in this country; that is, there are plenty of interurban roads on which bogie truck cars, with motors geared to the axles, are running up to sixty miles an hour without materially bad effects on the track. That method of construction has certain advantages which have been well expressed by the authors. Then there is the gearless type of motor, one which has appealed in many respects to every engineer who looks alone to the question of the simplicity of electric operation, because of the removal of every detail of side rod, extra bearings and gears as a necessary connection between the motor and the wheels. The gearless locomotive has some very distinct advantages, but also some distinct disadvantages. Space limitations, necessarily are somewhat exact, and part of the dead weight is carried on the axles; it may, however, be almost entirely spring-borne. The wheels are of moderate diameter, and the capacity of the machines, if built for low speeds, somewhat limited.

Then there is the side rod locomotive, which now seems to be coming into vogue, having been appropriated from steam railroad practice. There is also the combination of the geared and side rod locomotive, as illustrated in the drawing shown by Mr. Batchelder. One thing we must bear in mind, and that is the further we get away from direct gearing, or from gearless motors, the further we get away from simplicity. Every locomotive design must be a compromise; it cannot be one which is limited primarily by the kind of current one is going to use, nor on the other hand by the desire for simplicity; it certainly must not be limited by the demands of the steam engineer.

The latter has handed to us a morsel which we are rolling under our tongues with a good deal of avidity, and which is expressed several times in the paper presented this morning by the phrase "high center of gravity." I agree with Mr. Batchelder that the question of high center of gravity is less important than many other things in the construction of an electric locomotive, and I consider it perfectly possible to build a locomotive with a large disregard to the center of gravity, which will operate satisfactorily at either low or high speed. What is vital is that every wheel on a locomotive shall be independently shackled, if I may use that expression, so that it can have reasonable vertical and lateral movements to meet track irregularities without disturbing any more than necessary the balance of the locomotive, or the position of the superstructure. Of course, if wheels are rigidly mounted in bearings so that they cannot traverse in any direction without moving the whole mass of the locomotive we have a condition which is intolerable, no matter whether it is in a steam or an electric locomotive.

I will refer to the developments on one or two locomotives which will illustrate some practical points. Let us first consider the conditions which take place when a locomotive is running, both at slow and high speed. Every road is made up of tangents and curves. If we had a dead true surface and alignment, continuous rails and close gauge, it would not make much difference on a tangent whether high or low center of gravity was used, or what the springs were. With like conditions on a true curve, it would, after entering the curve, make little difference where the position of center of gravity is, because, after all, the flange of the wheel and the head of the rail are in intimate contact, and must remain so. Of course, we do not have these conditions, and therein lies the necessary for building locomotives to meet the actual conditions. However, with all the variations of surface and alignment, the track does not come up and hit the locomotive in the face, or give it a slap on one side. We have a pair of wheels slightly coned, and a certain lateral movement, traveling on two uneven rails, and as Mr. Batchelder has explained, it is impossible for two cones to so travel and maintain a central position, even on a true track. There is a tendency for these wheels to travel first one way and then another. The more slowly the locomotive moves the more difficult it is to traverse the rail, the faster it moves the more easily will the wheel traverse to one side or the other, the more severe will be the blow of the wheel when it does so traverse, and the heavier the blow which the flange will give to the rail when it recoils. You are all familiar with the early practice in regard to dynamos, putting a spring on the end of the armature to make the armature traverse back and forth to bring about an even wear of the commutator and brushes. The faster the armature traveled the easier it was to get it to move laterally. If you gave it too much play, a sharp push would drive it with a violent hammer blow against one bearing, and it would then rebound and strike the other. That happens on the locomotives at high speed on the rails as well as on the fast turning armature of a dynamo.

It has been said that with a high center of gravity, when you strike a curve the mass of the locomotive rolls over, the center of gravity goes towards the outer wheels, and the pressure on the outer rails is increased, thus increasing the rail resistance. I wonder if anyone who has made this statement has really investigated the problem to find out how far the center of gravity does travel, and what is the actual increase of pressure on the outer rail. If the rail is not properly banked and properly spiked to the ties, it would be better not to attempt to run a high speed locomotive on curves, because the increase of side pressure on the rail would be such that the ties would never hold it in place no matter what the increase of top pressure. The essential thing which takes place is the introduction of a time element before the flange has to take the entire pressure, as, of course, it eventually must.

On the New York Central, and also on the New York, New Haven & Hartford locomotives, certain characteristics early developed in practice which made it advisable to make some changes. The original Central locomotive had a fixed wheel base with four driving axles, and a pony truck at each end.

This truck may be described as a triangle, pivoted at the apex, and driving a single pair of wheels at its base. It was spring centered to normally maintain a central position. On the trial runs, at high speed on a tangent, some oscillation developed, with resultant side pressure on the rails. This was corrected by damping the motion of the truck, in other words, steadying it.

Shortly after the equipment was put into regular operation, there was a grave accident to a double header light train running at high speed, which some people have taken as a basis for a criticism of that type of locomotive, and various comments about the position of the center of gravity have appeared. A writer in an engineering magazine some time ago referred to this accident in a critical sort of way, not by name but by plain inference, and said that the responsibility for the accident was probably due to the low center of gravity. As voicing the admitted findings of every investigation committee, that statement is unwarranted. Referring to this accident, it is a curious fact that the locomotives never got away from the track; some of the wheels jumped the rails, but the coupled locomotives did not topple over, nor get away, notwithstanding their mass and the high speed at which they were traveling.

The same machines, without any change, were in operation for a long time subsequently, and are in operation to-day. Sometime since, however, a change was made which for some reasons I think was advisable. This did away with the single wheel truck, and substituted therefore a four-wheeled pivoted truck, an experience through which the steam locomotive has also gone.

On a curve such a truck yields easily, as it first turns on a pivot, instead of attempting to at once turn the mass of the locomotive. Then the forward wheel acting as a guide, with the rear as a fulcrum, helps the head of the locomotive around; in other words, the truck is the handle for turning. That is one improvement, but another was also introduced, and it was so good that our steam friends applied it to certain types of their steam locomotives; this was to give a greater lateral, but spring-resisted traverse to the wheels. I make it a practice, in going to and from my summer home, to ride on these locomotives to watch their operation. They run on old and new track, up to a speed of sixty miles an hour, and I find them very satisfactory.

It is a curious coincidence that on the New Haven road a train came within the closest shave of a disaster of even greater seriousness, when, running at high speed, two of the locomotives left the rails at the bridge at Greenwich, with the result, most fortunately, that but one person was killed. The wreck, however, was a pretty bad one. An immediate inspection of the track, following back a considerable distance, is reported to have disclosed some lateral displacement of rails. These locomotives, it will be remembered, have bogie trucks, spring suspended motors, and a somewhat higher center of gravity than the Central's. The difficulty developed has been largely corrected by extending the wheel base, and putting a pair of leading wheels on each truck. I think in this respect they are now running satisfactorily.

It has been stated that a non-symmetrical locomotive is essential to prevent oscillation in a horizontal plane on the track. I think the term is more or less misunderstood, but if we take the locomotive on a whole, I cannot agree with that conclusion. I believe that a symmetrical locomotive, whether it be of the articulated, or fixed wheel base, or any other type, is the electric locomotive of the future; the halves, of course, o an articulated or bogie truck locomotive can, and probably should be unsymmetrical.

The authors have made one statement to which I must take exception, and that is that from an operating standpoint the railway man would like to have one locomotive which will handle at the desired speeds the heaviest freight and the fastest limited passenger trains. That statement can hardly be intended to be accepted in the fullness of its meaning. While it may be true as to its desirability, if it were possible, in the matter of a steam locomotive, it is distinctly not true with an electric locomotive, because the multiple-unit system which I introduced some twelve years ago has made possible any desired combination of locomotive units under a single crew. But what I would call to your attention is the fact that under some conditions it is highly desirable to consider the possibility of a locomotive which will be interchangeable for freight and passenger service for certain *fixed units of trailing load*. For example, it may be desirable, with certain limiting mountain grade conditions, to have a locomotive which can operate, say, 400- to 450-ton passenger trains at one speed, and a 500-ton freight unit at half that speed, and then to consolidate these locomotives as desired according to the train make-up. It can be admitted that theoretically this is not the most economical plan on which to build locomotives per se, but the alternative, of course, is to build electric locomotives for passenger and freight service of distinct characteristics and sizes, and without interchangeability of parts. Now on most of our mountain grade divisions we have stretches of single track operation, with frequent sidings, to take care of opposing slow and fast freight and passenger traffic. Every single-track railroad, no matter how frequently it is equipped with sidings, is a difficult road to operate, especially if the traffic is heavy. On account of varying grades it is the practice when using steam locomotives, and it will be so with electric equipment, to add to and drop off locomotives as may be demanded by the varying duty, but in any case idle movements of locomotives is a thing to be avoided, as far as possible, because locomotive movements cannot oppose traffic without affecting materially the whole movement of through freight or passenger service on the line for a considerable period. Therefore if a locomotive can, without too great cost, be made available for interchangeable service, that is a desideratum to be seriously considered. It may result, of course, in a somewhat larger powered machine than is strictly required in the freight service, and a little heavier one than required for passenger service, but there will be a less total number because, instead of having two kinds of locomotives for each of which there must be reserve equipment, there will be only one kind, with a less total reserve equipment.

Another thing, it is cheaper to build a locomotive of a certain capacity than to build two of half power. The cost does not increase in proportion to the capacity. Another fact to be remembered is the importance of being able at any portion of the line to pick up or drop off a locomotive which shall be equally available for passenger or freight service.

I do not intend to take further time, but I want to emphasize two points. I am opposed to the idea that a very high center of gravity is vital to a successful electric locomotive. The idea has been handed down to us by our steam friends, and it has certain advantages. They cannot for many reasons get along without it on steam machines built for high speed. I also wish to emphasize the practical importance of sometimes having locomotives interchangeable for unit freight and passenger loads, as conditions may dictate the absolute necessity for such interchangeability.

A. H. Armstrong: In my opinion Mr. Sprague has not put the case too strongly in insisting upon the necessity of having freight and passenger locomotives interchangeable on mountain divisions where the maximum speeds are necessarily low. The weight of passenger trains may reach 600 tons trailing load and freight trains from 1800 to 2500 tons trailing load. It is desirable to move a train with a single locomotive unit if possible, but where grades approach two per cent on the better class of mountain divisions and even higher than this on some lines located before the requirements of modern freight traffic were thoroughly appreciated, it becomes necessary to consider two or more units per train in order to provide the draw bar pull required.

It is entirely feasible to consider an interchangeable type of locomotive running full speed with 600 ton passenger train units and half speed with a somewhat greater freight train load. A passenger train could be handled by a single unit while two or three units may be required with freight trains weighing two or three times as much.

The ratio of speeds, passenger and freight, may be taken at about 2 to 1 on mountain divisions, so that interchangeable locomotives of a uniform type offer a great advantage to the operating department on such grade sections as demand the use of helpers. Should such a uniform design of locomotive be adopted for passenger and freight service, a difficulty is removed with electric locomotives which is not experienced with steam helpers. The electric locomotive operates to best advantage at one or two speeds only while the steam locomotive can give its full horse-power output at nearly any speed, and hence is adopted to act as helper to either a passenger or freight train, working efficiently at the operating speeds of both.

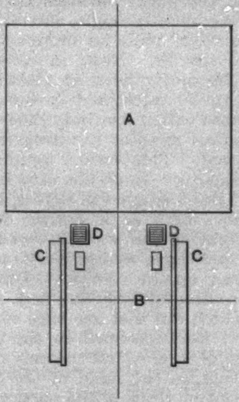
I think therefore that the matter of interchangeability is one of very vital importance and one that will be thoroughly appreciated by the operating department.

G. M. Eaton: Mr. Batchelder, in discussing this paper, was pleased to call it a mechanical paper. I wish to give you the reason why it seemed best to make the paper mechanical. In discussing Mr. Gasche's paper on Wednesday night, Dr. Steinmetz stated that in mill work the service, while far more severe than railway work, was a definite service. Now, in railway work, we find that the service of the motor from an electrical stand-point is very definite, and can be calculated to quite a degree of nicety, but we are confronted with an entirely different problem in calculating the mechanical stresses resulting from the negotiation of rails at high speed. This service produces maxima on the structure of the locomotive which are very hard to determine accurately. We can take a single rail defect, and assume all the conditions necessary, such as a known dead weight on the rail, spring-borne weight on the journal, speed of locomotives, etc., and under these conditions, we can work out a close solution of the stresses resulting on the framing. Unfortunately, however, when the locomotive strikes the first soft spot in the track, the conditions which are met are sure to be different from the conditions which were assumed in the calculations. We have then a nice set of figures, but the only real gain consists of the clearer conception, in the mind of the calculator, of what takes place in negotiating track of the particular characteristics assumed. This again is only the first step, as we must then consider the phase in which the various track irregularities occur, and the possible combinations with which we are confronted are legion. The application of exact mathematics is therefore impracticable in determining the precise dimensions of any given locomotive frame. Designers of electric locomotives must devote much study, however, to the means for minimizing the mechanical stresses on locomotive framing, and on track construction, and for this reason the paper under discussion is largely mechanical.

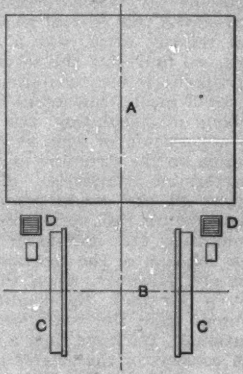
Mr. Batchelder stated that the dead weight on the axle was not productive of track destruction, so long as this weight was not in rotative unbalance. An examination of track maintenance on high speed interurban lines where dense traffic exists, shows room for improvement, and considerable experimentation is being carried out by some large operators' with a view to reducing the dead weight on rolling stock of this class.

Mr. Batchelder stated that the transverse distance between the semielleptic springs is of more importance than the height of the center of gravity. If this theorem could be substantiated it would constitute a severe arraignment against a low center of gravity locomotive with outside frames and a broad spring base. I wish to take exception to this theorem, however, for two reasons. Sketch No. 1 shows a locomotive with inside frames, and sketch No. 2 a locomotive with outside frames.

In each case, *A* represents the spring-borne parts of the locomotive, *B* the axle, *C C* the wheels and *D D* the springs. We agree at once that the arm with which the springs resist the swinging of the spring-borne parts is longer with the springs outside of the wheels; but, referring to Mr. Batchelder's illustration, you will note that as the locomotive has been laid out the advantage of the inside frames, namely, the short transverse spring base, has been very largely sacrificed by the short stiff spring. This is not inherent in the design, but attention is called to it to show that we must go further than the spring location, and must examine the spring characteristics. If the springs are designed with greater flexibility, then with outside frames, the desired angular displacement of the mass of spring-borne parts can be secured. This greater flexibility will mean somewhat heavier springs, and to that extent a heavier locomotive; but in the locomotive shown by Mr. Batchelder far too many sacrifices are made in order to gain the lighter spring. When countershafts and connecting rods are added, introducing reciprocating stresses, I am convinced that too much has been spent in payment for a narrow spring base.



Sketch No. 1



Sketch No. 2

The locomotive as shown has the great advantage of having the minimum amount of rotative masses tied together, that is, each driving axle has its own motor, and if the wheels on one axle wear a little faster than those on the other, it is not necessary to machine all the wheels. This seems to be the chief advantage of the design as shown.

The second reason for taking exception to Mr. Batchelder's statement, though this reason is of first importance, is that the swinging of the spring-borne parts is resisted first by their own inertia, and second by the springs. The springs cannot act until after motion has actually started, and when the center of gravity is close to the point of side restraint, the blow on the rails will have been delivered, and whatever mischief is going to occur will have taken place before the springs have a chance to get in their work. It is, therefore, of paramount importance to secure the maximum operative vertical distance between the center of gravity of the spring-borne parts, and the point at which the transverse blow is delivered to the spring-borne parts, and any other considerations, such as narrow or broad spring base, are entirely secondary.

Mr. Batchelder also remarked that the dead weight in steam locomotives designed for switching service did not produce harmful effects on the track. In studying electric switching service, if we set up as our ideal the track maintenance that is involved under steam operation we are looking at the problem from an erroneous standpoint. The maintenance in steam operated yards is heavy, but it is something to which operating men have become accustomed. They expect it, and they certainly get it. In considering the electric locomotive, we must remember that there is no incentive to electrification if we cannot beat the steam locomotive. We must beat them at their own game, or we cannot make good.

Referring to Mr. Sprague's remarks, I like the phrase that the locomotive and the track are in a state of matrimony and cannot be divorced. We can in fact carry the comparison a little further. We are led to believe that the compromise in many matrimonial relations is entirely one-sided, and in our American locomotive designs, we make the locomotive so rigid that all the compromising in the horizontal plane must be done by the track. This is not a fair proposition. In this connection I want to make a plea for plate frames on electric locomotives. We have not come to it in this country, but it is being done very successfully in Europe. They have frames which will yield, and which will take their share in the horizontal plane, and this results in a reduction of track maintenance. In this country the track maintenance, that is, the maintenance of rails, ties, culverts, and bridges—runs from about the same as rolling stock maintenance to as much as twice rolling stock maintenance. It is quite generally conceded that much more than half of the track destruction resulting from the passage of a train can be charged up to the locomotive. We can, therefore, imagine a locomotive in which maintenance is increased a little, while the maintenance of the entire system is very materially decreased and this with greater safety of operation. What seems to be necessary then is for the railway organization to be under one supreme head who will say to the heads of the various departments: "Now, gentlemen, get together". In this ideal organization, the various departments are not working each for themselves, but all are working for the railroad as a whole. This is the ideal to which large railroad organizations just the same as any other large organizations should bend.

Referring further to Mr. Sprague's remarks on center of gravity, he said, that it was entirely possible in his opinion to build a low center of gravity machine for successful high speed operation. I agree with Mr. Sprague that it may be possible. I do not believe, however, that it has ever been done.

Mr. Sprague referred to the Greenwich wreck on the New Haven Road, and I should like to add a little to his remarks. Mr. Storer and I left the Grand Central Station on the train immediately following the one which was wrecked, and arrived at the scene of the wreck within about 20 minutes of the time it occurred. The most impressive feature of this wreck to me was the way in which the locomotives held the train in tension after the derailment occurred. Instead of going through the bridge as a steam locomotive would probably have done, they carried every car safely over the bridge, although nothing but the steel bridge girders was left after the last car passed. The motors slid on the rails, so that the wheels could not cut deeply into the ties, and it was not until a Pullman truck had skewed around, causing its car to turn on the side, that any buckling of the train occurred. After this coach overturned, there was sufficient inertia in the locomotives to pull out a car drawhead and the locomotives and several cars ran 300 ft. further before stopping. The locomotives were then put on the rails and proceeded to the power house by their own power.

The number of deaths that have been caused by steam locomotive derailments, would have been materially decreased if the locomotives had been fitted with skid bars which would perform the duty so well fulfilled by the motors at Greenwich. A locomotive with high center of gravity and equipped with skid bars, would combine the desirable features of minimum derailing tendency, together with a minimum of destruction due to a derailment caused by a track defect.

N. W. Storer: Mr. Sprague took exception to our statement in the early part of the paper, to the effect that the superintendent of motive power and the superintendent of the operating department, would like, if possible, to have an absolutely interchangeable locomotive. He denied that statement, and then proceeded to prove it was absolutely necessary to have an interchangeable locomotive. I believe that the statement in the paper is correct; I believe fully it would be desirable to have an interchangeable locomotive if it is commercially possible. That is the whole point in the matter, and it is not necessary to try to prove at all that such a thing is desirable. If the operating man can afford to spend, or if the company can afford to spend, a large percentage more for locomotives for operating the trains over the road under a system which will make it necessary to have only one type of locomotive on the road, then it is commercially possible and quite practicable.

Elmer A. Sperry: The Institute is to be congratulated upon so timely a paper as that of Messrs. Storer and Eaton dwelling as it does upon the detailed construction of the heavier class of locomotives, especially with reference to the more general mechanical arrangement, distribution of weights, methods of power transmission, etc. In connection with mechanical design it might be well to point out one other phase, namely, its bearing upon the development of draw bar pull, upon the apparent adhesion and also upon tractive effort.

Many observations have been made in connection with slipping of drivers of locomotives, and of trucks, especially those employed in heavy service. There has also been considerable discussion with regard to the internal stresses and especially the redistribution of weights upon drivers under conditions of developing maximum draw bar pull.

In 1888, the writer drew attention to the very large apparent difference between the total coefficient of adhesion as between separately driven and coupled axles. There were cases where the latter showed repeated and continuous evidence of developing some 40 per cent more draw bar pull than the former. An investigation was started to ascertain the nature and extent of the difference between these two types. As the work progressed, it was at once seen that perfectly concordant results were being obtained and that a law governed the case which could be expressed by formula which was afterwards found to be a correct expression of the facts. This formula may be stated as follows:

Maximum draw-bar pull with independent axles.

$$P = \frac{W\phi}{20\frac{h}{b} + 1}$$

in which

P = the draw bar pull (maximum).
W = the weight (total) of locomotive in pounds.
ϕ = the coefficient of adhesion.
h = the height of bolster or drawhead.
b = the wheel base.

With coupled axles, either by rods or gears, the maximum pull is simply $W\phi$.

It will be observed from the foregoing that in any truck where the bolster height is *equal* to the wheel base, we are obtaining about 66 per cent of what we are really entitled to, and the coupling of the drivers will give us an increase of tractive effort of *one-half more*; in trucks where the wheel base is 1½ times the bolster height we are obtaining 75 per cent of what we are entitled to and the coupling would yield one-third more; and in trucks where the wheel base is twice the bolster height we are obtaining 80 per cent and the coupling would yield 25 per cent more. We thus see that this is not at all an insignificant matter but one of large magnitude.

FIG. 1

In 1890 the writer was engaged in manufacturing locomotives in which this principle of coupling the drivers to obtain maximum draw-bar pull was carried out to an extent quite unique at that time, and even since, namely, the class of locomotives having four axles or eight drivers connected with a single motor. See Figs. No. 1 and 2.

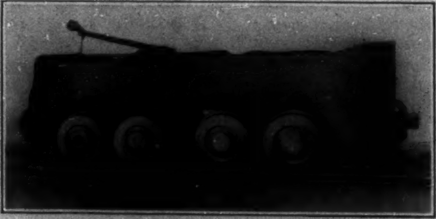


FIG. 2

In June 1892 the writer presented a paper before this body at its annual meeting in Chicago referring to experience and results obtained with this class of locomotive under service conditions. See Transactions for 1892, Vol. IX, page 397.

The drivers of the locomotives referred to were in groups of four upon each of the two trucks and were arranged so they could swivel in taking the short radius curves present in mines. The heavier type of these locomotives often work on curves as small as a 10-ft. radius. In this connection it is interesting to note that these locomotives were not only designed for heavy service but they were successful in a marked degree in accomplishing this purpose.

Fig. 1 is a photograph of a locomotive which was installed 1890 or 1891 and Fig. 2 is a photograph of the same locomotive after it had been continually in service for some eighteen years or more. This locomotive seems to be unique in that it has been in continuous service for a longer period than any equipment of which I am aware. In any event it is a noteworthy instance of an apparatus standing up under service which is acknowledged to be severe in the extreme.

More recently some interesting tests have been undertaken with a view to determining by experiment to what extent the redistribution of weights occurring upon two axle trucks affect the apparent adhesion. To this end, two locomotives were tested with a draw-bar pull at two heights above the rail, each locomotive, being 12 tons and motored to the point of easily slipping its drivers. The log of the test is as follows:

SLIPPING TESTS

14.5 in. height drawbar above rail

Amperes	Drawbar pull at slipping	Drawbar pull in per cent of weight
415	7000	29.15
412	7200	30
435	7500	32.3
	Average. . . 7316	30.48
Drawbar height 9⅝ in. wheel base 48 in.—33 in. wheels, steel tire.		
375	7100	29.15
410	7300	30.4
450	7500	31.3
418	7300	30.4
445	7700	32.15
445	7700	32.15
449	7500	31.3
405	7100	29.6
	Average. . . 7388	30.71

Tests were also made on a 12-ton locomotive equalized with the first as to total weight and having independently driven axles. Slipping took place at a drawbar pull of about 5250 lb.

with the 9.6-in. height of drawhead and 4850 lb. with 15.5-in. height of drawhead, averages of all the tests being as follows:

Height of drawbar above rail	Amperes	Drawbar pull at slipping	Drawbar pull in per cent of weight
15.5 in.	312	4950	20.6
9.6 "	334	5250	21.85

The average percentage of adhesion at point of slipping in the case of coupled drivers is about 45 per cent in excess of that in the two-motor equipment; same standard steel tires and identical rails were used in each case.

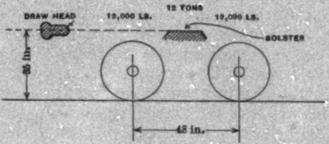

DRAW HEAD
12,000 LB.
12 TONS
12,000 LB.
BOLSTER
35 in.
48 in.

FIG. 3

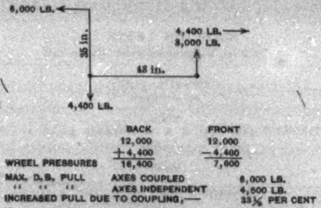

6,000 LB.
35 in.
4,400 LB.
6,000 LB.
48 in.
4,400 LB.
BACK
FRONT
12,000
12,000
+4,400
−4,400
WHEEL PRESSURES
16,400
7,600
MAX. D.B. PULL
AXES COUPLED
6,000 LB.
" " "
AXES INDEPENDENT
4,500 LB.
INCREASED PULL DUE TO COUPLING,—
33⅓ PER CENT

FIG. 3*a*

This indicates that the coupling of drivers effects favorably and to quite an unexpected extent the apparent coefficient of adhesion.

The nature of the shifting or redistribution of the weights as between the two axles upon an ordinary car truck or two-axle locomotive is very much greater than has been usually understood by builders of independently driven axle equipments, and the loss of capacity incurred has been generally underestimated. Ordinary practice with double motor street car or interurban trucks by the simple act of coupling would be entitled to between ⅓ and ¼ more total tractive effort than is obtainable with independent driving.

When a locomotive or truck is pulling a load, there are only two forces acting, which are external to the locomotive and independent of any internal forces. These two are the pull at the draw head or the bolster and the opposing pull of the wheel rims against the track. If these two forces are not in the line of travel, a tilting action will be produced, tending to elevate one pair of wheels, reducing the weight on them, and transferring additional weight to the other pair. As the draw head is always at some distance above the rail surface, there will always be shifting of loads on the drivers, due to the tilting effect of the draw bar pull.

Tests were undertaken to determine just the extent of this redistribution by apparatus shown in Fig. 4, namely, the front axle of a four-wheel locomotive weighing 12 tons, 48-in. wheel base, was placed upon rails *B* secured to a platform scale *A* the rear axle being placed upon the rails *C* and as between the pairs of rails the link *E* was supplied to take up the reaction without interfering with the action of the scale. The draw head *H* was rendered adjustable as will be seen in the table and was coupled with a rigid point *R* also adjustable as to height by a dynamometer *G*. The log of this test is as follows:

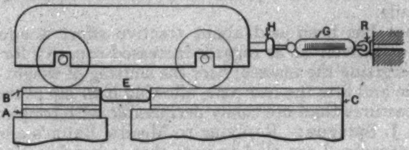


Fig. 4

Draw bar		Decrease in load upon front axle		
Height	Pull	Observed		Computed
			Probable limit of error in readings	
12 in.	6060	1520	160	1515
14 "	6100	1800	170	1780
16 "	6080	2000	210	2030
18 "	6010	2300	140	2280
20 "	6045	2700	180	2520
24 "	6030	3150	160	3015
35 "	6020	4500	190	4460

To give the foregoing analysis some definiteness, consider an example of a 12-ton locomotive with a 48-in. wheel base, the draw-bar being 35 in. above the track, adhesion taken at 25 per cent, we find that when the draw-bar pull is 6,000 lb. the weight upon the rear axle is 116 per cent in excess of the weight upon the forward axle. This is illustrated graphically in Fig. 3. Fig. 3*a* shows the force diagram, followed by deductions therefrom.

Summing up then, an electric truck or locomotive having two axles which are driven by independent motors has the weight on the forward axle reduced by an amount proportional to the drawbar pull; the pull it can exert is limited by the tractive effort of the least adhesive pair of wheels; because if one pair of drivers slips the other pair slips also.

If the two pairs of wheels be coupled together it is clear in case slipping occurs all the wheels must slip together. Therefore, the shifting of the weight due to the tilting effect of drawbar pull, does not decrease the maximum drawbar pull for although one pair of wheels gives a less pull than the other pair, the sum of the two is always constant, and since they must act together, the maximum draw-bar pull remains constant regardless of the tilting effect. The connecting of the wheels serves to automatically distribute the power of the driving motor between the two pairs of wheels in direct proportion to their respective adhesion to the rails.

All that has been said about tractive effort is equally true and quantitatively so as regards increased capacity for breaking or de-energizing the masses; here the shifting of weight loads the front axle and lifts the rear axle, allowing it to slip at much lower brake pressures than are easily permissible with coupled drivers.

Frank J. Sprague: Replying to Messrs. Eaton's and Storer's closing remarks, I am glad to note that it is acknowledged that it is " theoretically possible " to build a low center of gravity locomotive to run at high speed, and the possibilities of a flexible frame are suggested. That suggestion is quite in line with a thought of my own, and it is possible that in connection with some form of a linked truck construction, properly restrained or damped, there may be found one acceptable of solution of satisfactory locomotive construction.

Mr. Eaton in his reference to the New Haven wreck somewhat unwittingly and naively introduces a new element of discussion in locomotive design which gives emphasis to the statement that all such must necessarily be a compromise. He states that had the derailment occurred with steam locomotives the results would have been appalling, but that, as constructed, the axle-mounted motors helped to hold the locomotives in line with the track after the wheels had left the rails; in other words, motors with their axes coincident with axle axes prevented a disaster which would have been certain with motive power carried with a high center of gravity. The query naturally arises: What would have been the result had electric locomotives of the more recent vogue been used, that is, those with motors well up in the cab, driving by side and connecting rods through intermediary jack-shafts?

I will have to correct Mr. Storer's statement. He said that

I took exception to the author's statement to the effect "that the superintendent of motive power and the operative department would like, if possible, to have an absolutely interchangeable locomotive," and that then, while denying this statement, I proceeded to prove that it was necessary. The quotation is in error. I took exception to the statement as actually given in the author's paper, that "from an operator's standpoint it would be very desirable to have one locomotive which would be capable of handling at the desired speed any train from the heaviest freight to the fastest limited." I stated that this was not desirable, but that on certain roads, like some mountain divisions, it might easily be desirable within the ranges of speed which were required to have an *interchangeable locomotive for a "given unit weight,"* which would impose the same maximum drawbar pull, and to then combine these unit locomotives as required under multiple unit control. This is quite another thing, and its application becomes apparent when the makeup of passenger and freight trains in such service is considered.

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

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POWER ECONOMY IN ELECTRIC RAILWAY OPERATION—COASTING TESTS ON THE MANHATTAN RAILWAY, NEW YORK

BY H. ST. CLAIR PUTNAM

The power required for the operation of electric railways can be predetermined with great accuracy providing the cars or trains are operated in the manner assumed in the calculation of the speed-time and power curves employed for this purpose. Unfortunately, the cars are seldom operated as they should be, and although allowance for this variation is made engineers have long recognized that a material reduction in power could be realized in electric railway operation if the motormen could be induced or trained to operate the trains in a manner approximating the speed-time curve used in the preliminary calculations. It is proposed in this paper to describe some tests made on the Manhattan Elevated Division of the Interborough Rapid Transit Co., New York, in which a clock was used to record the amount of coasting employed in the operation of trains, the object of this device being to obtain from the motormen a better manipulation of the trains with the resulting economy in the use of power.

The clock as used in the tests consists of a clock mechanism manufactured for factory and office use for recording the time of employes. To the balance wheel escapement a braking device has been added, as shown in Fig. 1, which is lifted free from the balance wheel by an electromagnet which is energized only during the coasting of the train. This permits the clock to record the coasting time only. Each motorman is provided with an individual key which he inserts on taking charge of the train and again on leaving. The turning of this key records the motorman's number or initials and the time as shown by the clock mechanism; the difference in the time between the two records made by the key representing the total time of coasting during his run. The slip record is torn off by the motorman and turned in to the proper official. This is checked up with his running time, and the motorman is rated according to the percentage that the coasting time is of the total time of his run, due allowance being made for variation from the schedule. His individual rating is based upon the average results of a week or month as may be selected.

The electric circuits controlling the clock are interlocked with the master controller and the brake mechanism and arranged so that the coasting clock will start only after the two actions of turning the power on and then off. The connections used are shown in Fig. 2. The operation of the clock is stopped as soon as the air brakes are operated and the brake cylinder has started to move to the braking position. If, for any reason, after the brakes are applied, the air is released and additional coasting obtained before the train stops, this additional coasting is lost from the amount of coasting recorded unless power is again applied. This is not an important factor in normal operation as the actual amount of coasting of this character is small.

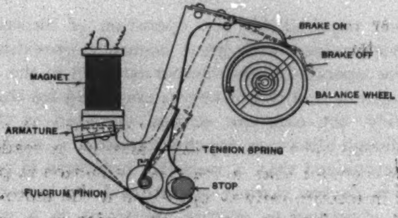


FIG. 1.—Details of clock mechanism

SPEED TIME CURVE CHARACTERISTICS.

While the principles involved in the use of speed time curve calculations in electric operation are well understood, for the purpose of making clear the economies in power consumption that can be realized from the better operation of trains, which it is the object of this clock to encourage, the following brief discussion of the various factors entering into electric operation is given.

Acceleration. The rapid acceleration of trains, providing the schedule speed is unchanged, results in an important saving of power for two reasons, first, the maximum speed reached is less with a high acceleration, and consequently the train resistance is somewhat less; second, and of much greater importance, is the fact that with a high rate of acceleration the speed at the start of breaking is less than with a lower rate and, consequently, the energy absorbed and lost in braking is less. The energy absorbed in braking is the essence of the whole subject, as in such train operation as that on the Manhattan system, and to a lesser extent in single car operation the increased train resistance resulting from the higher maximum speed due to a slow acceleration is unimportant and may be neglected. The only energy not utilized in useful work is

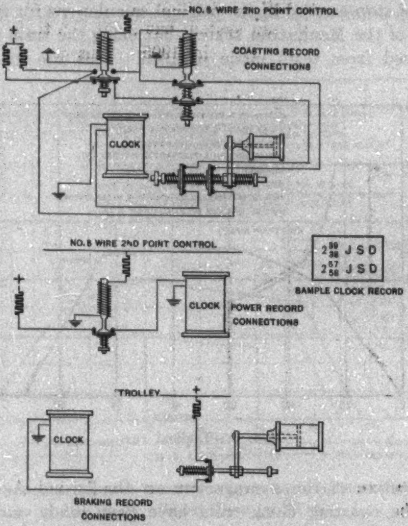

NO. 8 WIRE 2ND POINT CONTROL
+
COASTING RECORD CONNECTIONS
CLOCK
NO. 8 WIRE 2ND POINT CONTROL
+
CLOCK
POWER RECORD CONNECTIONS
2 39 38 J S D
2 57 56 J S D
SAMPLE CLOCK RECORD
TROLLEY
+
CLOCK
BRAKING RECORD CONNECTIONS

Fig. 2—Clock connections

that absorbed in the rheostats in direct current acceleration, the motor and control losses and the energy absorbed in the brake shoes.

The equipment provided naturally limits the permissible rate of acceleration, but within such limitations, a quick acceleration is one of the most feasible methods of reducing the power required in such service as exists on the Manhattan Railway.

Fig 3 shows the typical average run on the Second Avenue line, using the same rates of acceleration and braking and length of stop as used in the original calculations for the electrification of the Manhattan system but using the train resistance as derived from tests made in 1905. This run as shown is representative of the average run on the Second Avenue line where the coasting clock tests have been made, and is also representative of the average run of the entire Manhattan system. The distance between stations on the portion of the Second Avenue line tested, between Canal Street and 127th Street, is 1768 ft. as compared with 1763 ft. for the entire Manhattan system. In this typical curve the acceleration used is 1.33 miles per hour per sec. and the schedule speed is based upon the printed schedule of the road.

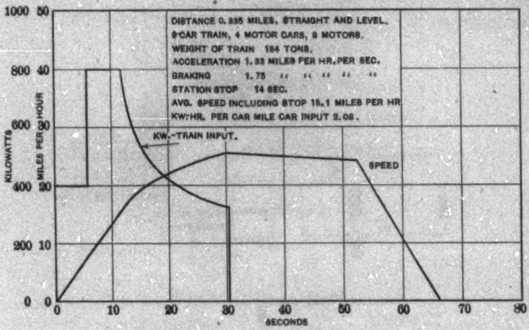


Fig. 3—Typical run

Fig. 4 shows the original speed-time curve used in the electrification of the Manhattan Division, and it will be noted is in close agreement with the curve shown in Fig. 3.

In Fig. 5 is shown the precentage increase in coasting time resulting from the increase in the rate of acceleration from 0.9 miles per hr. per sec. to two miles per hr. per sec., and the resulting decrease in power consumption, based upon an average run on the Second Avenue line. In the tests on the entire Manhattan system conducted on March 22, 1910, the acceleration of different motormen was found to vary from 0.9 miles per hr. per sec. to 1.47 miles per hr. per sec. Providing other factors of train operation remain the same (that is, the braking, running time and time of stop) the increase in the rate of acceleration from 0.9 to 1.47 miles per hr. per sec. will result in an increase in the percentage of coasting time from 0 to 40.5 per cent of the total time, and a saving of 36 per cent in energy consumption. A motorman on the Manhattan system on full runs will average about 600 car miles per day, and the energy used at the car with 0.9 acceleration will approximate 2.82 kw. hr. per car mile. As between these two motormen, therefore, providing the scheduled speed is maintained, the motorman who accelerated his train at an average rate of 0.9 miles per hr. per sec. will waste during the day 610 kw-hr. at the car. With 80 per cent efficiency to the power house, this becomes 762

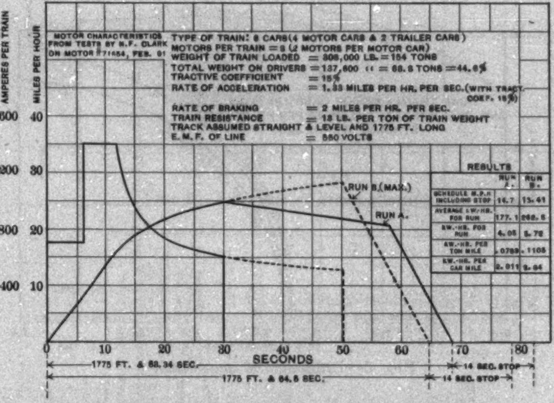


FIG. 4—Speed and power curves for train with eight motors
Gear ratio 71:18 = 3.94—Wheel diam. = 33 in.

kw-hr. This energy of course must be supplied from the power house where additional apparatus must be installed to meet the demand. In practice the full saving of power resulting from better acceleration is not realized, owing usually to the better running time made by the good operator. This results frequently in his having to wait for the train ahead and by so doing, a large part of the saving in power which should follow his good operation is lost. The use of this clock should result, however, in a material increase in coasting time under such circumstances, with a resulting reduction in power. The men will learn to gauge their trains, and instead of stopping for the man ahead, will utilize the surplus time in coasting. In order that schedules shall be maintained, however, some sort of penalty must be imposed to prevent the motorman from over-doing the coasting at the expense of the running time.

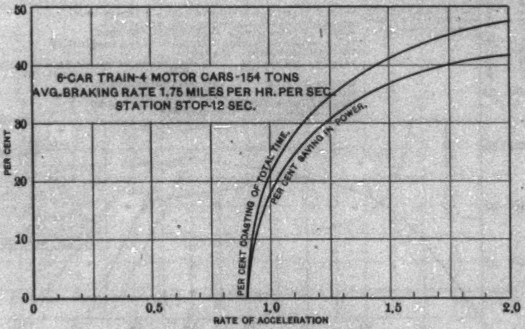


FIG. 5—Influence of acceleration

Series Running. In Fig 6, the effect of series running upon the percentage of coasting obtained and the resulting energy consumption is shown. It will be noticed that an increase in the percentage of coasting obtained by reducing the amount of series running does not effect a corresponding saving in energy. This is due to the fact that while the total time during which power is applied is increased and the time of coasting reduced by holding the controller in the full series position, say for four or five seconds, the actual energy used remains practically the same because the additional power required on account of the longer time of power application is offset in large measure, if not entirely, by the saving in rheostat losses owing to the reduced time that the rheostat is in circuit in passing to full multiple. This is shown in Fig. 7, which has been used in calculating the results plotted in Fig. 6. A limited amount of series running, therefore, is not objectionable, and under certain

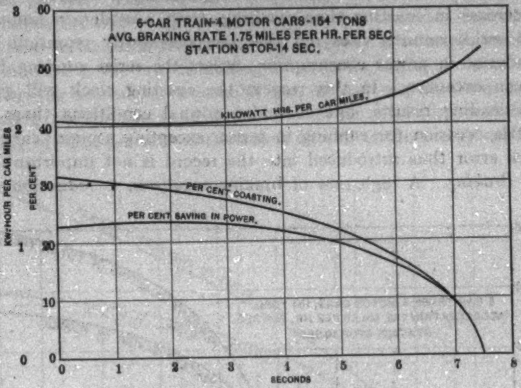


FIG. 6—Influence of series running

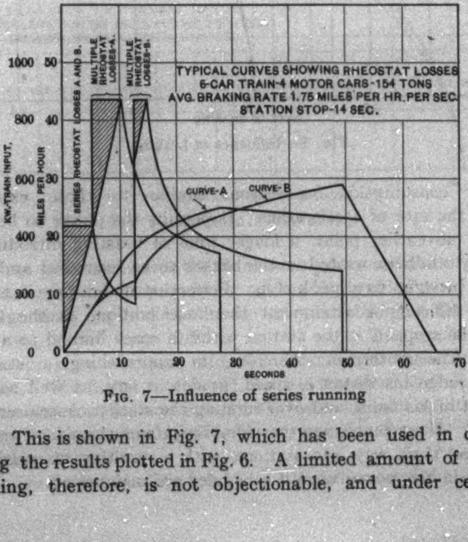


FIG. 7—Influence of series running

conditions it is better to run in series for a short time than to pass to the multiple position, especially where power is cut off almost immediately after the multiple position is reached as under certain conditions in approaching a station. The decrease in coasting time resulting from a moderate amount of series running does not therefore necessarily represent an increase in power consumption, unless the series running has been excessive. In this respect the coasting clock will give misleading results; but as under normal conditions there is little occasion for running in series, excepting around curves, the error thus introduced into the record is not important.

Braking. A high rate of braking results in a reduction in power consumption for reasons similar to those existing as to the rate of acceleration. It permits the power to be cut off at an earlier point, a longer time of coasting introduced, energy otherwise wasted in the brakes to be recovered and the train brought to a quick stop. Perfection in braking is much more difficult of attainment than acceleration, as the train must be stopped at the station within a space limited to a few feet. The motorman, therefore, in approaching a station must judge his distance, speed, grades, if any, as well as the weight of his train, and over-running the station causes serious delay. Many motormen therefore, operate on the side of safety and feel their way into stations, with a resulting material increase in the power used if schedules are maintained.

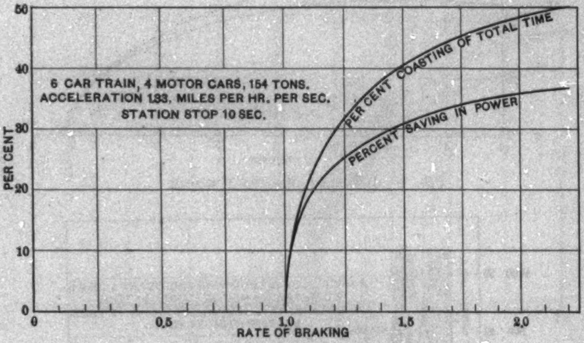


FIG. 8—Influence of braking

In Fig. 8, is shown the percentage of decrease in power on account of the increased percentage of coasting introduced by increasing the rate of braking from one mile per hr. per sec. to 2.25 miles per hr. per sec. These limits are frequently found in the operation of Manhattan trains. Two miles per hour per second is entirely practical as has been determined by carefully conducted tests. An increase in the rate of braking between the limits of one mile per hr. per second and two miles per hr. per sec. results in increasing the coasting to 48.5 per cent. of the total time with a saving of 35.5 per cent in the power as well as the energy used.

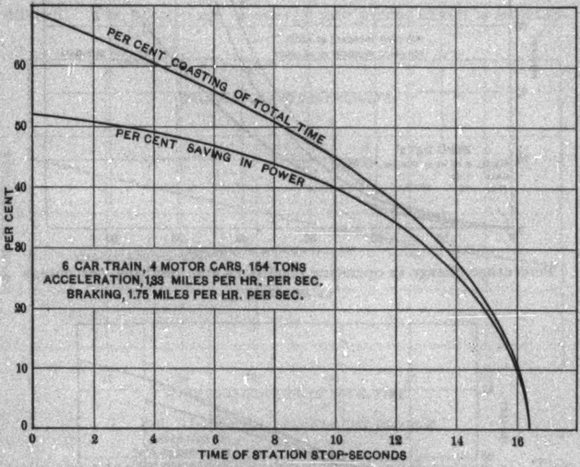
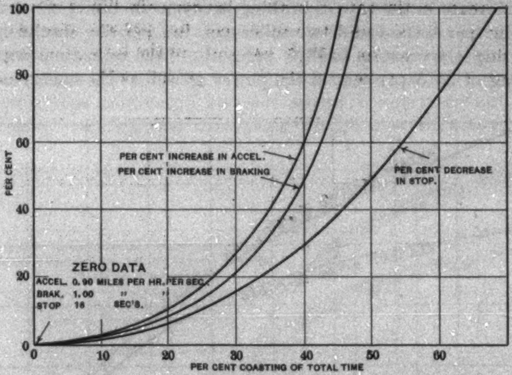


Fig 9—Influence of station stop

In the tests made over the Manhattan system on March 22nd, the trains were not equipped for getting the braking rate. The average time required by the motorman in bringing the train to a stop varied from 10.2 sec. to 20.2 sec. This would indicate approximate braking rates of 1.15 and 1.90 miles per hour per sec. The higher rate would increase the coasting time from 26 per cent for the lower rate, to 47.5 per cent, and result in the saving of approximately 280 kw-hr. per day by the better operator.

Station Stops. In Fig. 9 is shown the influence of the station stop. On the Second Avenue line, the average run is 0.335 miles and the maximum possible stop with the maintenance of the schedule, and with no coasting, is 16.2 sec., assuming an average run as typical, which is substantially correct for the purposes of the present discussion. A reduction in the time of stop to 10 sec. results in an increase in coasting time to 45 per cent of the total time and a reduction of 40 per cent in the power used.



Percentage change in operating conditions and resulting percentage of coasting

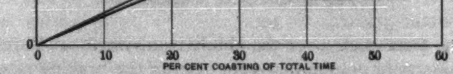


Fig. 10—Percentage reduction in power corresponding to percentage of coasting

Coasting. The amount of coasting which a motorman can obtain and still maintain his schedule, is obviously the result of the factors of operation above discussed. The ideal amount of coasting will result from the observance of all these factors. The theoretical coasting as shown on the typical curve is 27.5 per cent of the total time including stops. It has been shown in the above dicsussion that it is possible to obtain this amount of coasting and even to exceed it by changes in operation which are entirely within the range of practicability.

In Fig. 10, is shown the percentage of change made in these operating factors and the resulting percentage of coasting obtained and the corresponding percentage decrease in power. It will be noted that it makes but little difference which factor is altered. The percentage of energy and power saved is substantially the same however the increased coasting is obtained. This of course is to be expected. It is well to point out the very large saving in power consumption which results in reducing the stop from say 15 sec. to 10 sec. assuming that the schedule speed remains the same. This results in the saving of 25 per cent in power through the increased coasting thus made possible.

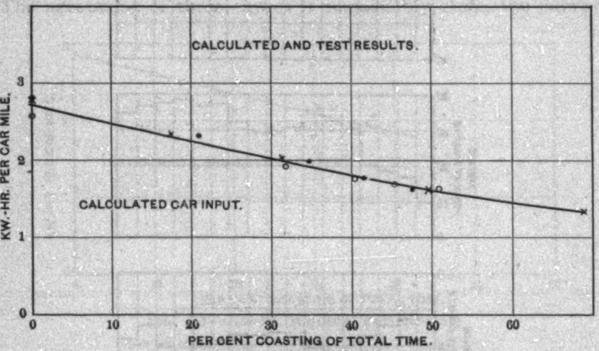


FIG. 11—Kw-hr. required per car-mile

Energy Consumption. In Fig. 11, the calculated energy required at the car, per car mile, is plotted under different conditions as to acceleration, braking and station stops as above discussed, these factors being plotted in terms of the resulting percentage of coasting obtained. This curve illustrates graphically the very material saving effected by any change in the methods of operation which results in an increase in the coasting time.

Second Avenue Test Results.

The results of the tests of the coasting clock which have been conducted on the Second Avenue line are plotted in Fig. 12. All trains on the Second Avenue line were equipped with coasting clocks, and the energy supplied to the section between 127th Street and Canal Street was metered by direct-current integrating wattmeters on the substation feeders. Corrections have been made for heaters and light, and the wattmeter readings corrected in accordance with frequent calibrations.

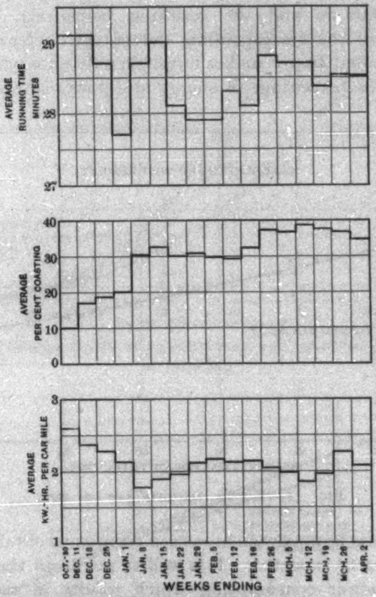


Fig. 12—Coasting clock tests on Second Ave line 127th St., to Canal St.—Oct. 30 to Dec. 11 before clock installation—Dec. 18 to Apr. 2 after clock installation

On account of the corrections that have to be made for heaters light, control and auxiliaries, the results obtained are necessarily approximate. Under these circumstances, therefore, the records are remarkably consistent and show graphically the material improvement in coasting which has resulted from the use of the coasting clock, and also the reduction in the energy required for the operation of the cars.

In Fig. 13, the kw-hr. required per car-mile as shown by these tests is plotted in terms of the percentage of coasting.

In Fig. 14, the average curve obtained from the Second Avenue tests and the average curve as obtained from our calculations, both expressed in terms of kw-hr. per car-mile, and the percentage of coasting obtained, are plotted on the same sheet. The agreement of these curves is remarkably close, the curves expressing the percentage of energy saved from the increased coasting practically coincide. Of course this is as it should be if the calculations and tests have been correct. Quantitatively, the kw-hr. per car mile obtained from the tests is about seven per cent higher than the calculations. The test results are measured at the substation while the calculations are at the car. The difference would represent the third rail losses, but it is believed that they are somewhat greater than this would indicate. The important feature contained in this curve is that on the Second Avenue line the increase in the time of coasting from 10 per cent as it was prior to the installation of the clocks to 38 per cent following such installation, resulted in a saving of 25 per cent in the energy required for traction. This result is in agreement with what should be expected from the theoretical calculations.

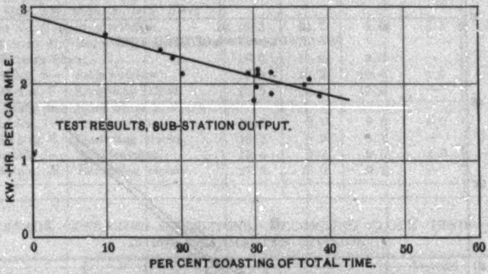


FIG. 13—Kw-hr. required per car-mile

MANHATTAN TESTS—MARCH 22, 1910.

On Second, Third, Sixth and Ninth Avenue Lines.

In order to compare the operating conditions existing on the Second Avenue line with the conditions on the other lines of the Manhattan system, on March 22nd a test train was run in actual sevice over all divisions of the Manhattan system. A seven-car train composed of four motor and three trail cars was used. Each trail car was equipped with one of the record-

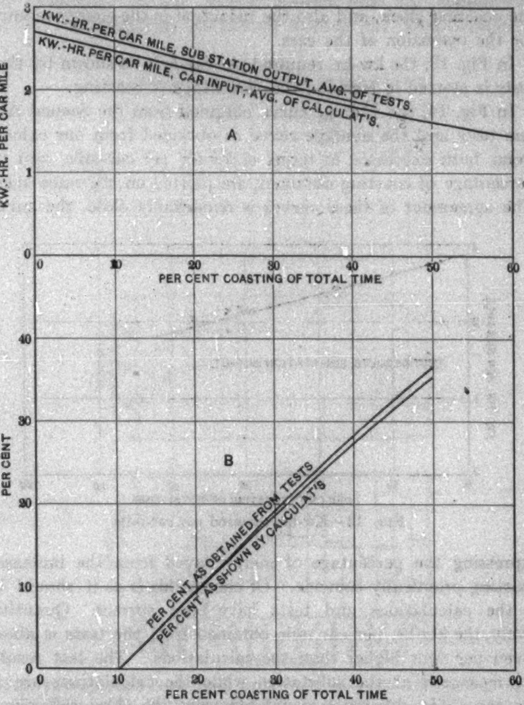


FIG. 14

A-Kilowatt-hours per car-mile

B-Percentage reduction in power resulting from coasting

RECORDING CLOCK TESTS—MARCH 22, 1910. MANHATTAN DIVISION INTERBOROUGH RAPID TRANSIT COMPANY

	Power applied min.	Coasting min.	Braking min.	Stops min.	Total time by watch minutes
Second Ave. 129 to S. Ferry					
Test No. 1— Stop watches.........	11.7	18.8	5.3	7.0	42.3
8:01 a.m. S.— Recording clocks......	11.9	19.6	6.3		
Test No. 2— Stop watches.........	11.1	19.8	4.4	3.7	39.1
8:45 a.m. N.—Recording clocks (To 127th St. only)..................	10.5	20.9	4.9	—	—
Test No. 5— Stop watches.........	12.0	15.8	5.0	4.8	37.5
1:23 p.m. S.—Recording clocks......	11.0	17.0	5.7	—	—
Third Ave. Bronx Pk. City Hall					
Test No. 3— Stop watches.........	27.1	7.5	11.3	10.4	56.7
9:45 a.m. S.—Recording clocks......	26.0	6.3	12.5	—	—
Test No. 4— Stop watches.........	21.1	15.4	9.8	8.9	55.1
10:53 a.m. N.—Recording clocks....	19.8	17.8	10.0	—	—
Sixth Ave. 155th St. to S. Ferry					
Test No. 6— Stop watches.........	19.2	10.7	8.6	8.1	46.8
2:6 p. m. N.—Recording clocks (Start Battery Place)..................	18.0	11.0	9.0	—	—
Test No. 9— Stop watches.........	19.9	10.3	10.4	6.6	47.9
4:23 p.m. S.—Recording clocks......	18.5	11.5	12.5	—	—
Ninth Ave. 155th St. to S. Ferry					
Test No. 7— Stop watches.........	19.9	8.1	8.6	6.0	42.9
2:55 p.m. S.—Recording clocks......	18.2	8.2	8.7	—	—
Test No. 8— Stop watches.........	19.4	9.1	9.3	4.5	43.2
3:39 p.m. N.—Recording clocks.....	17.8	10.0	9.3	—	—

AVERAGE OPERATING CONDITIONS. RECORDING CLOCK TESTS—MARCH 22, 1910. MANHATTAN DIVISION

	Average Length of run feet	Average acceleration seconds	Average Power applied seconds	Average coasting seconds	Average braking seconds	Average stop seconds		Average total time seconds
						Station	Signal	
Second Ave.								
Test No. 1-S...	1723	11.4	26.0	41.7	11.9	13.2	2.4	95.2
Test No. 2-N...	1752	11.5	25.7	45.6	10.2	8.8	—	90.3
Test No. 5-S,..	1723	10.3	26.7	35.0	11.2	9.9	1.3	84.1
Third Ave.								
Test No. 3-S...	1767	14.6	42.7	11.8	17.9	16.8	—	89.2
Test No. 4-N...	1767	12.8	33.2	24.2	15.6	13.2	1.3	87.5
Sixth Ave.								
Test No. 6-N...	1841	14.5	38.5	21.4	17.1	14.3	2.5	93.8
Test No. 9-S...	1833	11.4	38.4	19.9	20.2	11.2	2.0	91.7
Ninth Ave.								
Test No. 7-S...	1833	17.2	41.1	16.7	17.8	11.3	1.6	88.5
Test No. 8-N...	1833	19.1	40.2	18.7	19.3	9.3	0.6	88.1

ing clocks. These clocks were connected as shown in Fig. 2. One clock was used to record the coasting time, the second the time of power application, and the third the time of braking. Stop watch records were also made of the time of series running and total power application, time of coasting, time of braking and time of station and signal stops.

The result of these tests are tabulated on the preceding page.

SECOND AVENUE TESTS

The results of the tests over the Second Avenue line reduced to an average run are plotted in Fig. 15 in what we have called "Running Charts" for each of the three tests on this division. These curves approximate speed-time curves in form, but naturally as the different factors which enter into the characteristics of the curve are averages, the resulting curve does not pretend to give the correct area and distance. The curve is but a picture of the average operating conditions of the run.

It will be noted that motorman *S* in test No. 2 obtained 50.5 per cent coasting, the largest amount recorded during the day. Of the three tests on Second Avenue, motorman *O* in test No. 5, obtained the smallest amount of coasting, 41.4 per cent and carried power for the longest time, 31.6 per cent, yet he was the best operator of the two. If he had used the same time in making the run as motorman *S* in test No. 2, it would have been possible for him to obtain as high as 58.5 per cent coasting as shown by the broken line on test No. 5, and he could have cut his power application down to 22.2 per cent with a saving of 8 per cent in energy and as compared with motorman *S* in test No. 2. The good results in test No. 5 were obtained with an acceleration of 1.47 and braking of 1.85 (approximate) as compared with an acceleration of 1.35 and braking of 1.75 (approximate) in test No. 2. The rate of braking indicated on these curves is approximate only, as the average braking includes the signal braking between stations and at curves in addition to the braking at station stops. The slope of the braking curve, however, indicates quite accurately the relative rate of braking used by the motorman.

The motormen who operated the trains in the tests on the Second Avenue line were selected men and the runs were made to illustrate what could be accomplished after a thorough training of several months. The average coasting obtained in the three runs is 45.2 per cent. This indicates a reduction in

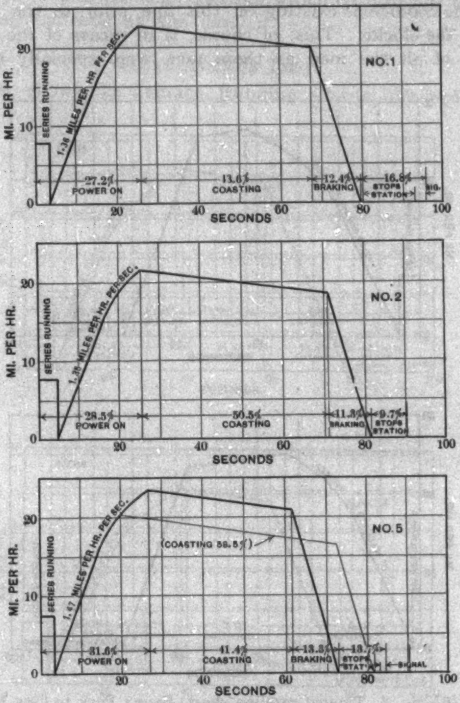
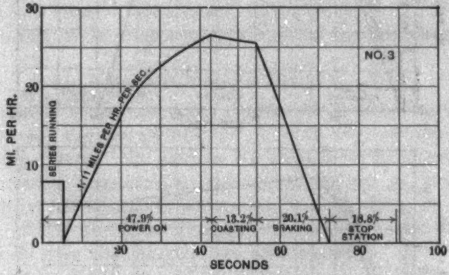


FIG. 15—No.1. Typical running chart, 129th St. to South Ferry—
8:01:20 a.m. to 8:40:43 a.m.—Motorman S—
Schedule time 35 min—27 runs—Average run 1723 ft.—
Average speed 12:3 miles per-hr.
No. 2. Typical-running-chart, South Ferry to 127th St.—
8:45:20 a.m. to 9:24:23 a.m.—Motorman S—
Schedule time 34:5 min. 26 runs—Average run 1,752-ft.—
Average speed 13:2 miles per hr.
No. 5. Typical-running-chart 129th St. to South Ferry—
1:23:15 p.m. to 2:0:45 p.m.—Motorman 0—
Schedule time 35 min.—27 runs—Average run 1,723 ft.—
Average speed 13.9 miles-per hr.

power consumption amounting to 34 per cent as compared with the conditions existing on this line prior to the installation of the clocks. This, of course, is in excess of the average saving of all the men as these men were specially selected.



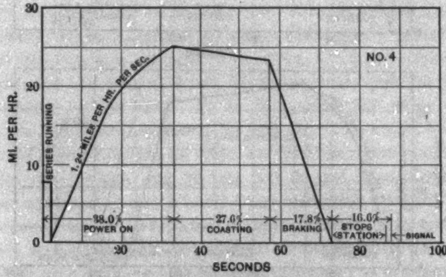


FIG. 16—No. 3. Typical running chart, Bronx Park to City Hall—
9:54:04 a.m. to 10:50:46 a.m.—Motorman C—
Schedule time 51 min.—38 runs —Average run 1,767 ft.—
Average speed 13:5 miles per hr.
No. 4. Typical running chart, City Hall to Bronx Park—
10:53:45 a.m. to 11:48:50 a.m.—Motorman G—
Schedule-time 51 min.—38 runs—Average run 1,767 ft.—
Average speed 13.8 miles per hr.

These tests also bring out strongly that any system of rewards or ranking of the men based upon coasting time should include a penalty for overrunning the scheduled time.

The tests on the Second Avenue line, as observed, show an average of 45.2 per cent coasting which corresponds to 1.70 kw-hr. per car-mile at the car.

THIRD AVENUE TESTS

Fig. 16, shows the average Running Charts obtained from the tests on the Third Avenue line. In the Third Avenue tests, the run south was made with the motorman whose turn it happened to be. This run shows 13.2 per cent coasting. The run north was made with an experienced man and shows 27.6

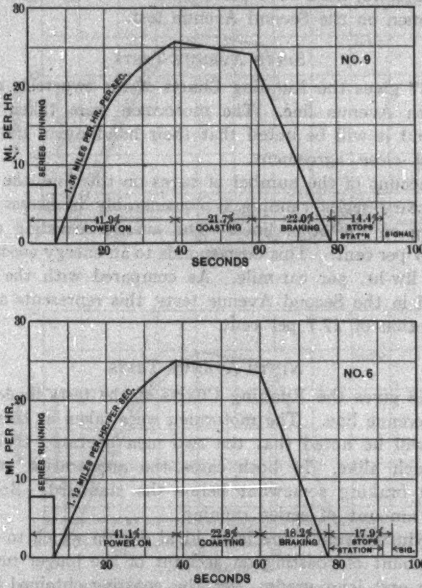


FIG. 17—No. 9. Typical runing chart. 155th St. to South Ferry—
4:25:07 p.m. to 5:13:00 p.m.—Motorman C—
Schedule-time 43 min.—31 runs—Average run 1,833 ft.—
Average speed 13.7 miles per hr.
No. 6. Typical running chart, Battery Pl. to 155th St.—
2:06:37 p.m. to 2:53:25 p.m.—Motorman W—
Schedule time 4:15 min.—30 runs—Average run 1,841 ft.—
Average speed 13.4 miles per hr.

per cent coasting. The difference is due mostly to the difference in the rate of acceleration, but partly to the braking rate and partly to an excessive amount of series running in test No. 3.

These two runs show an average of 20.4 per cent braking which indicates 2.22 kw-hr. per car-mile at the car. These men, therefore, used 30.6 per cent more energy than was used by the men on the Second Avenue test.

SIXTH AVENUE TESTS

Fig. 17 gives the Running Charts of the two tests made on the Sixth Avenue line. The motormen were taken as they came, and it will be noted that their handling of the train is in fairly close agreement.

On account of the number of turns on this line, the amount of necessary series running is considerably in excess of that obtaining on the other lines. The average coasting obtained was 22.3 per cent. This corresponds to an energy consumption of 2.17 kw-hr. per car-mile. As compared with the average obtained in the Second Avenue tests, this represents an excess consumption of 27.7 per cent.

NINTH AVENUE TESTS

Fig. 18 gives the Running Charts of the tests made on the Ninth Avenue line. The motormen were taken as they came, and it will be noted that the two men operated their trains very much alike. In both cases the acceleration was poor and the braking somewhat below the standard. Both used a large amount of series running.

The Ninth Avenue line is an ideal one on which to obtain a large amount of coasting on account of the longer runs, easy schedule and long grades, yet the coasting obtained by these two men was but 18.9 per cent and 21.2 per cent respectively. and averages 20.1 per cent. As compared to the average obtained in the Second Avenue tests, this represents an excess consumption of 31.8 per cent.

CLOCK RECORDS ON THIRD, SIXTH AND NINTH AVENUE LINES

In the tests conducted on March 22nd, the motormen were conscious of being under observation by the test crew as well as by their own road officials, and under such circumstances they naturally tried to do their best. The results obtained therefore, cannot be regarded as representative of actual conditions, but can be taken as fairly representing the best that these men could do, and therefore, as illustrating the knowledge of the motormen in general. The tests were too few in number, however, and the conditions under which they were made were such that they are not regarded as representative.

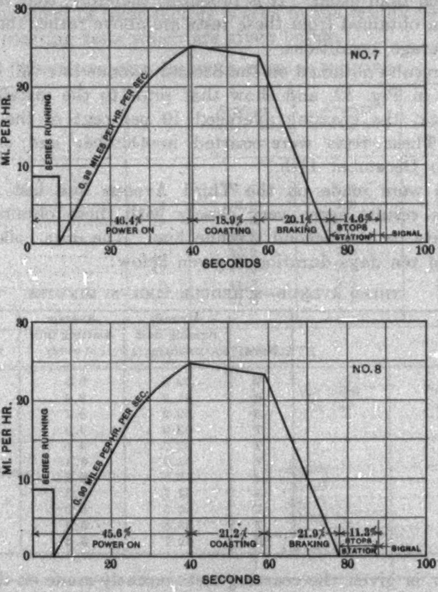


Fig. 18—No. 7. Typical running chart, 155th St. to South Ferry—
2:55:07 p.m. to 3:38:00 p.m.—Motorman M—
Schedule time 40 min.—29 runs—Average run 1,833 ft.—
Average speed 14.1 miles per hr.
No. 8. Typical running chart, South Ferry to 155th St.—
3:39:20 p.m. to 4:22:35 p.m.—Motorman C—
Schedule time 40 min.—29 runs —Average run 1,833 ft.—
Average speed 14.2 miles per- hr.

In order to determine the fair average conditions as to coasting existing on all divisions of the system, tests were made on the Second and Third Avenue lines last fall and two trains equipped with clocks were put in regular service this spring on the Sixth and Ninth Avenue lines.

The average of these results should be fairly representative of the coasting conditions at present, as well as prior to the installation of the coasting clock on the Second Avenue line. The men soon become aware of the trains equipped with clocks, however, and consequently are more careful in the operation than usual. It is probable, therefore, that the coasting data obtained from these tests are above rather than under the average conditions.

The results obtained on the Second Avenue line will be found plotted in Fig. 12, and show that prior to the installation of the clock, the coasting averaged 10 per cent of the running time. These tests were started in October and continued daily to December 11th.

Tests were made on the Third Avenue line last summer and the results agree very closely with those obtained at a later date on the Second Avenue line. The data collected on a test of ten days duration is given below:

THIRD AVENUE—SCHEDULE TIME—51 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
July 16	7	52.9	6.3	11.8
July 22	6	51.3	8.4	16.4
July 27	3	52.2	3.7	7.1
July 28	7	52.9	3.3	6.2
July 29	7	52.3	3.2	6.1
July 30	7	52.8	5.1	9.7
July 31	4	53.6	6.2	11.5
Aug. 2	5	52.7	6.3	11.9
Aug. 3	7	52.6	5.9	11.2
Aug. 4	7	53.3	5.9	11.1
Average	60	52.7	5.4	10.2

Below is given the coasting tests recently made on the Sixth Avenue line. It will be noted that the amount of coasting agrees very closely to that existing on the Third and Second Avenue lines prior to the installation of the coasting clock.

SIXTH AVENUE—SCHEDULE TIME—43 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
March 28	16	45.9	6.1	13.2
March 29	10	46.8	5.7	12.2
March 30	10	46.7	5.2	11.1
March 31	8	45.9	5.3	11.5
April 1	2	44.0	3.6	8.2
April 2	10	46.2	5.2	11.3
Average	56	46.2	5.5	11.9

The Ninth Avenue line as already mentioned, furnishes an ideal one upon which to obtain a large amount of coasting, on account of its undulating grades, longer distance between stations, and easy schedule. In addition to this, the average train on this line is made up of four motor cars and two trailers instead of four motor cars and three trailers, as on the other lines. The effect of these factors is seen in the results obtained from the coasting tests which are given below.

NINTH AVENUE—SCHEDULE TIME—40 MINUTES

	Runs	Average running time minutes	Average coasting time minutes	Per cent coasting
March 28	5	37.7	4.9	12.9
March 29	12	38.0	6.9	18.0
March 30	13	36.5	7.8	21.4
March 31	12	38.0	7.6	19.9
April 1	15	37.3	7.0	18.7
April 2	12	37.0	7.9	21.3
April 3	8	41.7	8.3	19.9
Average	77	37.8	7.4	19.1

SUMMARY—COASTING DATA

	Car miles per day	Per cent coasting
Second Avenue	28,863	10.0
Third "	79,403	10.2
Sixth "	46,571	11.9
Ninth "	33,826	19.1
Average	188,663 (total)	12.2

From the above tests it is probable that the average coasting obtained on the Manhattan system approximates 12 per cent of the running time. On account of the fact that the motormen are very alert to discover that they are under observation, it is probable that the actual amount of coasting is below, rather than above, this amount.

RESULT OF EQUIPMENT WITH COASTING CLOCKS

In the table below is given the average coasting obtained during five weeks on the Second Avenue line, where the coasting clock has been in service for slightly over three months. The average run on this part of the Second Avenue line, as already pointed out, closely approximates the average run for the entire Manhattan system.

SECOND AVENUE LINE—COASTING DATA. COASTING CLOCK INSTALLED FOR THREE (3) MONTHS

	Average running time minutes	Average coasting time minutes	Per cent coasting
Week ending March 5	28.7	10.5	36.8
" " " 12	28.7	11.1	38.8
" " " 19	28.5	10.8	37.7
" " " 26	28.5	10.6	37.0
" " April 2	28.4	10.1	35.4
Average	28.6	10.6	37.1

VALUE OF POWER REDUCTION THROUGH COASTING

The result of these calculations and tests shows that an increase in the percentage of coasting from 12 per cent to 37.5 per cent as shown above, will effect a saving of 24 per cent in the power required for traction.

COASTING VS. POWER MEASUREMENTS

The various factors that enter into the operation of the train have been analyzed with a view to determine which is the preferable element to measure. The choice practically narrows down to the measurement of either the power input by wattmeter or time of application by means of a clock arrangement, or the measurement of the time of coasting. It is believed that it has been made clear that whatever good results are obtained from the better operation of the train by the motormen can only result in the saving in power through the increase in the coasting time. Coasting results in the recovery of energy already used, and hence is the key to the problem. The coasting clock, therefore, gives a direct measure of the energy recovered by the motormen and as this recovery can also only be made by cutting off the power application sooner, it is believed that it is the most effective element in train operation to measure. At the same time it concentrates the motorman's attention on that element of operation which is the direct reason for the reduction in power which results from changes in the methods employed as to the other factors of operation.

This subject has been discussed at some length, as it brings up some interesting features of electric train operation. Preliminary schedules for electric operation in service similar to that on the Manhattan system, usually included from 25 to 30 per cent coasting, partly for reasons of power economy and partly to provide a factor of safety, as it has been realized that motormen do not operate their trains in compliance with the calculated speed-time curve. It is believed that the use of the device here described will not only insure the better operation of trains but will result in a material reduction in the power used.

The writer is indebted to Mr. L. B. Stillwell and officials of the Interborough Rapid Transit Company for the use of material embodied in this paper.

DISCUSSION ON "POWER ECONOMY IN ELECTRIC RAILWAY OPERATION COASTING TESTS ON THE MANHATTAN RAILWAY, NEW YORK". JEFFERSON, N. H., JULY 1, 1910.

John B. Taylor: I wish to ask Mr. Putnam if the motormen have found any way to beat this clock. I have not studied the diagram very carefully, and wonder if by turning on the power and turning it off again immediately at a station, it would be possible for the motorman to make the clock record during the time of the stop.

A. H. Armstrong: The problem of reducing energy consumption of a train is now pretty well understood, and I am very glad to see that active steps are being taken to keep a record of the performance of the motorman. It is well known that rapid acceleration decreases the amount of power consumed in frequent stop service, but in connection with that I would ask Mr. Putnam if he has noticed any increase in the ragged appearance of the substation load curve, and whether the more rapid acceleration used has called for any appreciable increase in substation and distribution system capacity.

Rapid acceleration may be carried too far where the service is infrequent, and it is possible to approximate its benefits without unduly increasing the maximum demand per train by resorting to a very high rate of acceleration in series and a lower rate with the motors connected in parallel. The advantages in so doing are two fold. It affords a quicker get away from the station with a corresponding abrupt angle of the speed-time curve, and reduces the maximum demand of the train and the motors in multiple running where it will most effect the distribution system and the operation of the motors themselves.

N. W. Storer: This paper has been of great interest to me. It is certainly a great satisfaction to feel that railway operators are at last beginning to realize the necessity for careful instruction of their motormen, and the saving that can be effected by proper operation. I believe that ignorance of the correct theory of operation is at the bottom of a large part of inefficient operation of electric railways. I have great faith in the motormen of interurban railways, and believe that if they are properly instructed, they can usually be relied upon. The great trouble is not so much with the motormen as with the managers of the road.

The installation of the "coasting time clock" described by Mr. Putnam will automatically instruct the motormen as to the best method of operation, and will be a good check on them as well. This method seems to me to get at the root of the matter much more quickly than the use of the wattmeter. It has the great merit of giving the men practically one point to look out for, and if this one is kept constantly in mind, the efficiency of operation will undoubtedly be high.

L. B. Stillwell: The facts set forth in the paper which Mr. Putnam has presented are an excellent illustration of what may be called effective team work between the consulting engineers and intelligent, alert operative men. I quite agree with Mr. Putnam's suggestion that at times we are hard on the manufacturers, in asking them to do almost the impossible. Of course, it is right to obtain the best that is reasonably practicable, but in doing that we may be overlooking many opportunities for economy in our own particular province in the field of construction and operation. The value of the economies effected by the introduction of this coasting clock on the Manhattan Elevated Railway system in New York is extremely striking. The power bill of that division of the Interborough Rapid Transit Company approximates $4,000 a day. A reduction of twenty-five per cent is about $1,000 a day, and you can see what that means. That has been accomplished by the joint work of the consulting engineers and operating men. The particular device used is due to the operating men, who have very intelligently developed something which is effective with their motormen. They propose to establish a system of premiums, which will further stimulate the attention and effort of the motormen.

Referring to Mr. Armstrong's question, the effect has not been to increase the average acceleration, but to bring it up to what it was intended to be, not beyond what the substation was designed for, but to the standard of economy which the engineers originally intended in laying out the plant. The desirable coasting period, as determined theoretically is thirty-five to forty seconds, the actual performance without the clocks being only twelve. This condition of affairs required the introduction of a clock. The clock has brought the performance up to the economic standard set by the engineers.

Wm. McClellan: There is a point to which he refers, that I would emphasize in connection with Mr. Putnam's paper, and that is the question of lengthening out the coasting time at the end. My own experience is that it is difficult to get a motorman to brake a train in what you might call the theoretically efficient manner; in other words, the habit which the motorman has of putting on the brakes long before they need be put on, then letting them go, then applying them again, and letting them go again, etc.; and I think that this is a loss which the measuring of the coasting time would eliminate more effectively than any other power consumption on the train which is measured. The saving can hardly be estimated, but is very great, which could be secured from the elimination of this habit of the motormen of applying their breaks and releasing them without occasion. That point is referred to in the paper, but not emphasized.

Frank J. Sprague: The striking facts set forth by Messrs. Putnam and Stillwell are a somewhat tardy contribution to the efficiency of coasting and quick acceleration which have been advocated since the South Side Elevated road in Chicago was first operated electrically. No reference has been made to automatic acceleration. When developing electric elevators and establishing the secondary control of controllers, I quickly realized that the personal element of a man was a small thing to rely upon for perfect service; that to get even torque on motors, reasonable strains on apparatus and a proper consumption of the supply of electricity, whether from a battery or a dynamo, the movement of the controller should be automatically accelerated and controlled. In the case of the South Side road, where the first multiple trains were installed, every main controller was fitted with a throttle which permitted the controller, under control of the master switch, to automatically accelerate to either series or multiple position, at a rate determined by the amount of current passing through the motors.

Economy of operation between stations depends primarily on two things; first, the quickest, safest and most comfortable acceleration, and second, the maximum safe and comfortable braking. The necessary amount of coasting is determined by the relation of these two. Automatic acceleration, now used on most recent equipments, performs the first function. That, however, is not enough, for while it removes from the motorman the personal element in starting his train, he is still privileged to continue to accelerate, coast for a short distance, and meddle with the brakes in any way he sees fit. The introduction on the Manhattan Elevated Railway of the coasting clock, to check the operating engineers on that road by determining the coasting time, is an excellent method of insuring a fuller measure of the value of coasting on a railroad. Mr. Stillwell has pointed out that it means saving $1,000 a day in power supply in the case of that one road. It also means something else, for referring to the figures given in Mr. Putnam's paper, I estimate that it would have effected on the Manhattan Elevated Railroad a saving of about 5,000 kilowatts in initial equipment, which represents a capital cost of anywhere from $500,000 to $750,000.

L. B. Stillwell: The figure I mentioned, viz., $1,000 a day, was meant to include interest on the capital cost as well as the car operating cost.

N. W. Storer: There was one point I neglected to mention in my previous remarks, and that was to speak of the series operation which Mr. Armstrong brought out so well. I agree with him heartily, and want to mention that it is perfectly possible to arrange the control, as has been done in some cases, to accelerate at a high rate in series, and any other fixed rate in parallel, so as to get the automatic acceleration which certainly is most desirable.

G. H. Hill: The acceleration portion of the speed-time curve is undoubtedly the most important with relation to the comfort of passengers and the economy of power. As Mr. Sprague pointed out, the adoption of automatic control removes this element from the influence of the motorman. As Mr. Storer mentioned, and as in operation in different places, this can be accomplished either at a constant current per motor, or at different predetermined rates in series and in parallel. That leaves only two elements of the curve which may be varied according to the judgment of the motorman.

If there were developed a practicable system of automatic braking (that is, a system wherein the braking effort is applied automatically as some function of the speed), the proper amount of coasting would, for a given schedule, take care of itself. Such a system of braking is somewhat complicated, and has not to my knowledge been used. With heavy trains, operated at speeds higher than now usual in a service requiring frequent station stops at a high rate of braking, it may possibly become a desirable or necessary feature.

Mr. Putnam's apparatus aims at the desired result by checking the coasting period, so as to induce the motorman to reproduce as nearly as possible the proper predetermined run cycle. The results seem to fully justify the complication and expense incident to its use. The arrangement of circuits and apparatus illustrated can I think be somewhat simplified and perhaps improved so as to be self contained and quickly applied to any car. The scheme certainly seems more practicable than the use of recording wattmeters, which are sometimes advocated for a similar purpose.

H. St. Clair Putnam: Several questions have been raised in the discussion of this paper which I will take up as briefly as possible. Mr. Taylor has inquired what precautions have been taken to prevent the beating of the clock by the motormen. This subject has been carefully considered by the designers. The diagram of the connections used for measuring the time of coasting is given in the paper. All electric contacts and magnets used in the operation of the clock are placed inside the case excepting the contacts which are made and broken by the operation of the brake cylinder. The latter are placed beneath the car. It is impossible to cause the clock to register coasting time without manipulating these contacts and at the same time having the controller handle in the second position or beyond, so that the motors as well as the clock will receive current. This is practically impossible for the motorman to accomplish. In addition to these precautions, in the case of the Manhattan Elevated system, the clocks are placed on the trailers, entirely out of reach of the motorman.

Mr. Taylor suggests that it might be possible for the motorman to beat the clock by turning power on and then off again immediately during the time of stop. While this, of course, is physically possible, yet it is impracticable because the actuating current is taken from the second point of control, which the motorman cannot reach without moving the train, and if he attempts to hold the train with the brakes, the clock is immediately stopped. If he can coast into the stop the clock will continue to register, but as such a stop results in the largest possible return for the energy used, owing to the energy otherwise lost in braking being used to move the train, the motorman is entitled to all the credit he can obtain in this manner. Practically it will be impossible for the motorman to make such stops and maintain the schedule, and in most cases it is practically impossible for him to make a stop without using his brakes, or stand still with his brakes off, because of grades.

Mr. Sprague, Mr. Armstrong and Mr. Storer have commented upon the subject of the reduction made in the amount of energy required by increasing the rate of acceleration. This has long been recognized. The possibility of its accomplishment in electric operation, and especially in multiple unit operation, is one of the most important advantages obtained in electric traction. The amount that this acceleration can be increased is limited, in any particular case, by the capacity of the equipment provided. As Mr. Stillwell has pointed out, however, it is not the function of this clock to increase the acceleration over the amount for which the equipment has been designed, but to obtain in practice the acceleration that was contemplated by the engineers in selecting the electrical equipment for the system, including motor cars, substations, feeders and power house. As all operating men know, and as our tests of the Manhattan Elevated show, the motormen do not attain in practice the acceleration that they are instructed to use. This clock has demonstrated that under the guise of increasing the coasting time, the advantages of rapid acceleration are forced upon the motormen, and the desired result attained.

Mr. Sprague and Mr. Hill have called attention to the benefits to be derived from automatic acceleration and that this would take one of the elements of the speed-time curve out of the control of the motorman, and assist in accomplishing the results desired. This is true, but one of the most important factors in the operation of the Manhattan Elevated system which resulted in increasing the amount of the coasting obtained in our tests was not so much an increase in the rate of acceleration, as improvement in the manipulation and handling of the trains.

This is illustrated by the fact that since the clock has been installed the motorman coasts up slowly behind a preceding train, when delayed by the train in front, instead of coming up full speed and then applying the brakes and coming to a stop as is usually done. This results in a material reduction in the energy used. Furthermore, the motorman soon finds that he can increase the amount of coasting and still maintain his schedule if the stops can be cut down, so he gets after the rest of the train crew to cut the stops as short as possible. As most of the crew are candidates for promotion, they are forced to respond.

Mr. Hill has also called attention to the possibility of automatic breaking, and Mr. McClellan has emphasized the importance of braking. If automatic braking were possible of accomplishment in a practical manner it would be most desirable. The proper braking of a train on such a system as the Manhattan Elevated is the most difficult part of the operation to obtain from the motormen, as judgment, skill and experience are required. Such an automatic device, if perfected, must of necessity permit the motorman to increase or decrease at will the rate of braking fixed by the automatic device, so that he can make his proper stop at the station platform. There are many practical difficulties in the way of the attainment of this result, though I will not say that it is impossible of accomplishment. Experience gained on the Manhattan system, however, has shown that the installation of the coasting clock has resulted in a radical improvement in braking as well as in acceleration, and that with this device, the theoretical speed time curve as used by the engineers in designing the equipment of the road can be closely approximated in the average results obtained, while some of the motormen by careful handling of their trains obtain even better results.

Mr. Armstrong and Mr. Storer have suggested that a rapid acceleration can be used in the series position, and a reduced rate in multiple, with the result that a fair average rate of acceleration can be obtained without compelling the substation to take care of such high peaks as would otherwise result if the same running time were made by using a uniform straight line acceleration for both control positions. There are many advantages in this method of operation, especially for interurban roads where the substation capacity is limited, and the trains infrequent. With the short headway used on the Manhattan system, however, the advantages of such a method of operation largely disappears. As already has been pointed out, the strength of gears, motor capacity, and the comfort of passengers, limit the practical rate of acceleration that can be used. In all cases, if this rate of acceleration can be employed in series, the average of both the power and energy required will be reduced by using the same rate of acceleration in multiple, for the simple reason that in a large system such as the Manhattan, all apparatus in the power house, substations and feeders can be operated at their heating and economical limitations, and any reduction in the energy used therefore results in a corresponding reduction in the apparatus required.

In the case of interurban roads and other roads of limited service, the improvement made in the operation and handling of equipment resulting from the installation of some such device as this coasting clock, might result in the ability to reduce the rate of acceleration used during the multiple period, with a resulting reduction in the average rate of acceleration, and a corresponding reduction in the peak load on the substation feeder system and power house, without reducing the scheduled speed. This again, however, would have to be balanced against the cost of the increased energy used. In most cases, especially where the service and stops are frequent, the higher rate of acceleration usually will be found most economical.

P. A. Bancel: Mr. Putnam points out clearly the key to economical operation of heavy city railways by saying that "the energy absorbed in braking is the essence of the whole subject." One means of reducing the amount of energy lost in braking is to retard the speed of the train by causing it to climb a grade. By running a train up a slight grade as it approaches a station, and down a similar and equal grade as it leaves the station, an interchange of kinetic and potential energy is secured and corresponding saving in power obtained. The principle involved is evidently similar to that employed with elevators, where counter weights retard or brake the speed descending, and assist the motion in ascending.

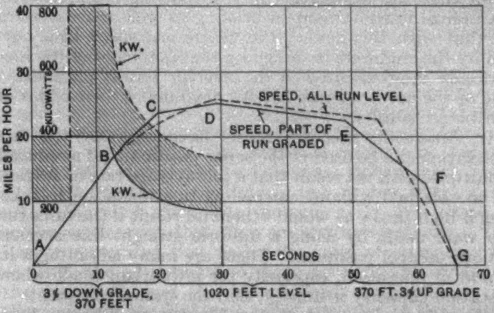


FIG. A.—*A-B*, acceleration due to gravity plus motors; *B-C*, acceleration due to gravity plus motors on motor curve; *C*, end of 3 per cent down grade; *C-O*, acceleration on level, due to motors on motor curve (resistance all cut out); *D-E*, coasting on level track, retardation due to train resistance; *E-F*, coasting on 3 per cent up grade, retardation due to gravity plus train resistance; *F-G*, braking, retardation due to brakes, gravity and train resistance.

The saving produced by applying such a principle to electric railway traffic can best be shown by an example. Taking the train of Fig. 3, assume that the train leaving the station at time zero, is on a 3 per cent down grade. Since the force of gravity acting on the train is 154 tons, the accelerating force in the direction of motion will be $3/100 \times 154 \times 2000 = 9240$ lb. Now the force necessary to produce an acceleration of 1.33 miles per hr. per second (the acceleration of Fig. 3) is 18620 lb., as found from the well known expression, force = mass × acceleration. Since the 3 per cent grade is providing 9240 lb. accelerating force, it is now necessary to obtain only 18620–9240 or 9380 lb. accelerating force from the motors of the train. This is approximately 50 per cent of the original force necessary.

If then a train of the same weight were equipped with motors of but half the capacity, and drew only half the current from the line, the same resistance acceleration would be obtained on a 3 per cent down grade. This line, *A B*, shown on Fig. *a* is therefore identical with that of Fig. 3 of the paper.

All the resistance being cut out, the motors accelerate on the motor curve. Assume now that the 3 per cent down grade lasts till the end of the 20th second. From the time that the resistance is all cut out at the 12th second, up to the 20th second, the train is also being accelerated by the component of its weight, 9240 lb., acting in the direction of motion. At any second the accelerating force along the motor curve is proportionate to the kilowatt input divided by the speed. Assuming that at any instant with the motor equipment reduced by half, the accelerating force due to the motors is also reduced by half, figures are obtained from which the accelerating curve from *B* to *C* and *B* to *D* was calculated. From *B* to *C* acceleration is due to both motor force and gravity, and the actual velocity at any instant was obtained from the acceleration, which in turn was derived from the total accelerating force at the same instant. This accelerating force has been seen to be the sum of the constant 9240 lb. and the variable motor accelerating force. The curve from *C* to *D* is the plain motor acceleration curve.

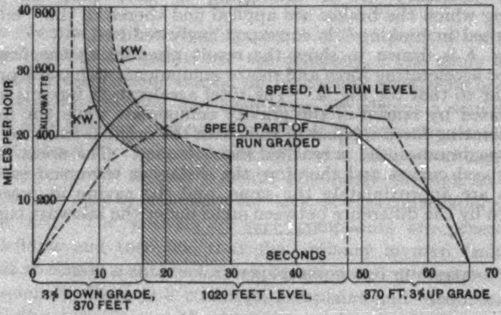


FIG. *b*

By assuming 3 per cent down grade for 20 seconds, followed by level track, it is seen that the speed time curve obtained coincides very closely with the original. The rest of the chart is constructed by following similar calculations. The line *E F* is the braking due to the upgrade alone, while $F\ G$ is that due to both the up grade and the actual brakes. The point E was determined by trial to make the area under $E\ F\ G$ equal to that under $A\ B\ C\ D$. Thus the distances of up-grade and down-grade are equal. From the areas the actual distances are calculated as 370 ft., 3 per cent down grade, 1020 ft. level track and 370 ft., 3 per cent up grade. By assuming these distances, and grades, the whole speed time curve is made to coincide very closely with the original, so that their areas and therefore the total distances traversed in either case are the same.

The saving to be obtained by such a see-saw arrangement of grades has already been indicated. For the same rate of acceleration about half the kilowatt-hour input would be required, and only half the motor capacity would be needed. The kilowatt-seconds input saved where grades are used is shown by the shaded area and this is roughly ½ that originally necessary. It is interesting to note that the time during which the brakes are applied and therefore the " energy absorbed in braking " is correspondingly reduced.

Fig. *b* is drawn to show the result when using the original motor accelerating force and motor equipment, with track profile similar to that for Fig. *a*. The total accelerating force is again increased by reason of the gravity component while the motor accelerating force is equal to that with the original train, so that the maximum speed is reached much sooner. The areas under the speed curves and therefore the distances traversed in both cases are approximately the same, and the saving in power is shown by the difference between areas under the kilowatt curves.

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A METHOD FOR DETERMINING THE ADEQUACY OF AN ELECTRIC RAILWAY SYSTEM

BY R. W. HARRIS

The adequacy of a railway system is often a point of contention between the public and the company. The many lawsuits and investigations carried on by various regulating bodies is evidence of this fact, and such cases are always a source of trouble and expense. In many instances they are unnecessarily brought about by "chronic kickers" who take advantage of every opportunity to gain political popularity through an attack on the railway company for lack of cars, unreliability of service, etc. The answers to such complaints are generally so indefinite and technical that the ordinary layman finds it difficult to obtain a satisfactory explanation and understanding. Consequently, there is a continual complaint and disturbance among the traveling public because, perhaps, of alleged insufficient accommodation and the lack of a fair knowledge of the railway business.

As a matter of fact, companies often do not know definitely whether or not their systems are really serving the public in the best possible way. A necessary requisite of successful operation is to satisfy as conveniently as possible the requirements of the public that are established by a natural development of the community. The petty whims and fancies of the few are not serious factors in determining the adequacy. There are, however, certain habitual movements (barring a certain amount of indiscriminate travel by pleasure seekers, shoppers, etc.) which the traveling public forms that are comparatively stable in character and magnitude. They are the natural resultant of the various routes automatically established by the passengers. These movements occur daily and, in general, do not fluctuate in direction, for when the habit of making a "usual" trip over a certain route is once formed, it is seldom broken.

Every city has its manufacturing, wholesale, retail, and residence districts definitely located and these are changed only very gradually through years of growth and development. Consequently, the origins and destinations, except in a few cases, will not change materially.

The extent to which these prevailing movements are met is an important index of the adequacy of a railway system. Adequacy involves many delicate and technical questions of a more or less intangible nature. The extreme fluctuations in the amount of travel caused by different weather conditions, etc., make it impossible, as well as impracticable, to endeavor to meet all peak conditions of travel with satisfaction to all.

It is the purpose of this paper to bring out certain conditions which were encountered while making an investigation into the adequacy of The Milwaukee Electric Railway & Light Company's railway system for the Railroad Commission of Wisconsin, under the direction of the author, and to show how they were considered.

If a system is adequate, it must be sufficient to care for the reasonable demand of the traveling public in its various forms as well as to be in line with a well directed plan to care for present and future business economically. The routing of the cars that serves the largest number of people by the most direct route, at times when the traffic requires it, free from delay and with a sufficient number of sanitary cars so the average amount of traffic will be comfortably cared for, is highly desirable. These are very material factors in establishing an adequate system. A failure to provide any one of these accommodations will result in an attack, sooner or later, on the company for giving poor service. In most cases the conditions become exaggerated in the minds of the public through the lack of sufficient understanding of the business and, as a result, the company may sacrifice a part of the public's good will.

A system that satisfies the above requisites, carried to such an extent that the amount of investment required and costs incurred will not exceed a reasonable proportion of the earnings as well as to be a convenient link in a systematic plan arranged to care for future growth of business, might be said to be an adequate system.

The particular layout of a city and the franchises that may be secured enters the case to such an extent that it is often impossible to establish a direct route for all classes of passengers. These, together with many other difficulties, may make it impossible to secure an adequate system in the strictest sense of the term. An adequate system, from a practical point of view, is one that will handle the demands of the public in the shortest time by the most direct route with as little distortion of headway as possible, and with the least inconvenience to the passengers. Reliability of service is necessary. If the regular headway is frequently distorted to such an extent that the public suffers from the lack of regularity in the service, the system is inadequate, since it does not supply the reliability characteristic. The nature of these various conditions are radically different, and are peculiar to each city. Each company must study its own characteristics of service and determine its own method of handling various conditions. There is very little reliable data to be had regarding the detailed features of service. However, considerable has been written regarding general conditions in various localities.

The data and curves shown in the following pages are not the result of a theoretical deduction but are compilations of data taken by a trained force of inspectors along a definite, pre-arranged outline so designed as to show the various conditions as they exist in the system's operation. All data were observed on the street and compiled so as to show clearly the features of operation. No dependence has been placed upon any records of the company that were obtained in the form of trip sheets, and general data collected by supervisors, etc. The effects of numerous personal elements of the uninterested trainmen, who so often fail to appreciate the importance and use of such information, do not enter.

A general study of the movement of people during the day revealed the fact that there were four distinct periods during which the majority of people travel. These periods were very easily determined, for during such times the amount of travel was much greater than that during other portions of the day. They were designated arbitrarily as Period No. 1, Period No. 2, Period No. 3 and Period No. 4, and were found to occur, respectively, from 6:00 a.m. to 9:00 a.m.; 11:00 a.m. to 2:00 p.m.; 5: p.m. to 8:00 p.m.; and 10:00 p.m. to 11:00 p.m.

The adequacy of the system will be measured by the conditions existing during these periods since all features of traffic will be encountered in their greatest degree of effectiveness. The rate of flow of passengers, so to speak, resulting in the largest demand for cars, is greatest during these periods as well as the amount of congestion in the down town districts, all of which are material factors in distorting headway. During these periods, certain classes of passengers are easily agitated and become abusive to the company on account of inconveniences experienced due to late cars, overcrowding, etc. This feeling becomes intensified with any neglect on the part of the company to rectify and improve such conditions.

A careful investigation of each line and a determination of the characteristics during the peak periods are the first requisites that lead to a definite measure of adequacy.

A definite plan was outlined for conducting a study of the system that would determine the practical working conditions as mentioned above and so arranged that all similar observations made by the inspectors would be on the same basis. Each inspector was assigned a line to observe and was directly responsible for securing accurate and reliable data. He made a preliminary study of the line with a view of locating the principal points where the most people boarded and left the cars. These were selected as points of observation. A sufficient number of points were chosen for each line that would give the main characteristics. As a rule, from 6 to 14 or 15 points were selected, depending upon the traffic of the line.

The following data were observed for all cars on each line going in each direction, at all points of observation, and throughout each period, with possibly a few exceptions. This method required the inspector to spend practically a day at each point. As a matter of fact, however, his time was distributed along the line so as to give characteristics that would embody the various conditions occurring during a long period of time:

Time car arrived at point of observation.
Direction car is going.
Number on car body.
Total number of passengers.
Total number of passengers in front vestibule.
Total number of passengers in car body.
Total number of passengers in rear vestibule.
Number of passengers leaving car.
Number of passengers boarding car.

Class of passengers.

Conditions of vehicular traffic.

Conditions of pedestrian traffic.

All data could be obtained by count or close estimates excepting the class of passengers and condition of vehicular and pedestrian traffic. These were recorded according to the following arbitrary scheme:

Passengers.

1st class—Professional and business people.
2nd class—Clerks and shoppers.
3rd class—Laborers.

Vehicles and Pedestrians.

1st condition—Few in number.
2nd condition—Considerable amount but not enough to cause delay.

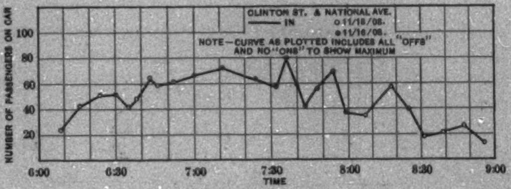


FIG. 1.—Fluctuations of traffic—Oakland-Delaware line (south end) Period 1

3rd condition—Sufficient amount to cause much delay to cars.

At first glance it might seem that the amount of data to be taken of each car going in each direction is more than could be expected without sacrificing accuracy, and especially when the time spacing of cars is often as short as ten seconds; this feature, however, is overcome by practice in making observations. As a matter of fact, the inspectors became so efficient that the data was found to be 95 per cent accurate by test, which is sufficiently close for this class of work. This data does not embody sufficient information to establish all characteristics of the lines and it was found necessary to obtain various miscellaneous data of a general character. This general investigation was made of each line by the inspector to supplement the detailed data which had been secured by the service inspection.

Considerable time was spent in observing the operation of the line and its surroundings in a casual way with a view of determining any special features of the line that were characteristic of all lines, as well as those that were more or less local. The following gives an outline of the data required of the inspector in making the general report of his line:

(a) Divide line into characteristic sections (bound each roughly) and discuss each as to class of passengers, time of travel and probable destination.

(b) Locate various origins of passengers along line, obtain as closely as possible their destination and probable route. (Refer to factories, etc).

(c) State transfer points and give an idea as to the number (in percentage of passengers leaving car from which transfer is made) transferring to other lines (name the lines) in various directions.

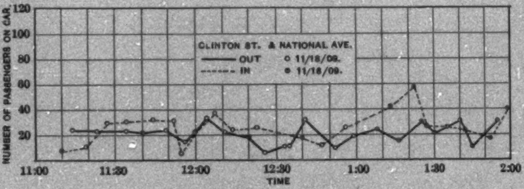


Fig. 2.—Fluctuations of traffic—Oakland-Delaware line (south end)—Period 2

(c) Determine the attitude of the public served by the particular line as regards the service given by the company. This can be done by several casual conversations with passengers.

(e) Make a few specific observations (record count) of the movement of the passengers (seated passengers to vestibule and vice versa) in the car as it approaches the stop in downtown and outlaying districts.

(A few continuous trips through the districts under investigation during the various periods will probably give the information desired.)

The above included a general reference to the transferring question but, on account of the impossibility of determining the number of people leaving or boarding the car who hold transfers, this data had to be supplemented by a study and classification of the transfers actually collected by the company

(Fig. 11). On account of the endless amount of work thus involved, it was considered advisable to classify the transfers taken on a representative day and qualify this information by that secured in the general report.

An investigation of the headway that existed in the various districts along the lines is embodied in the requirements of the detailed study. For the sake of comparison and assistance in determining what was the safe minimum time spacing of cars for any section of track, certain observations were made in various cities in the middle west where conditions were somewhat similar to those found in Milwaukee. The result of these observations are shown in the following pages.

The above gives a general idea of the method used to secure the field data. There are, however, many minor details omitted that perhaps would be of interest but, for the sake of brevity, they are left to be inferred from the various tables, curves, etc.

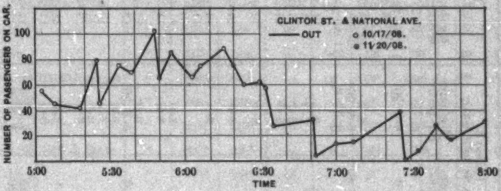


FIG. 3.—Fluctuations of traffic—Oakland-Delaware line (south end)—Period 3

While there was a marked difference in the amount of traffic during the various periods of maximum travel, as compared with other times of the day, yet the traffic was, by no means constant during any period. As a matter of fact, the traffic during one portion would be radically different from that of other portions of the same period. Fig. 3 gives an example of the curves showing the fluctuation of traffic during the periods of maximum travel with time as one axis and total number of passengers as the other. The most characteristic point of each line was selected and a similar traffic fluctuation curve plotted. These curves show a very pronounced difference in the amount of travel between practically two parts. A reference to Fig. 3 shows a maximum period from 5 p.m. to 6:30 p.m. and a minimum period from 6:30 p.m. to 8 p.m.;

TABLE I. SUBDIVISIONS OF PERIODS OF CONGESTION FOR VARIOUS LINES

Line	Place	Period I 6 a.m. to 9 a.m.		Period II 11 a.m. to 2 p.m.		Period III 5 p.m. to 8 p.m.		Remarks
		Maximum sub-period	Minimum sub-period	Maximum sub-period	Minimum sub-period	Maximum sub-period	Minimum sub-period	
1. Wells-Farwell	Jackson & Biddle	7:30–9	6–7:30	11:40–12:40 12:45–2	11–11:40 12:40–2 11–12:45	5–6:30	6:30–8	E. End-Out E. End In
Wells-Farwell	11th & Wells	6–8 7:30–8:30	8–9 6–7:30 8:30–9	12:45–2 11:45–12:45	11–12:45 11–11:45 12:45–2	5–6:30	6:30–8	W. End Out W. End In
2. Fond du Lac-National 3. Walnut-National 4. 8th Ave.-3rd St.	Walnut & Third Reed & National Reed & Greenfield	6–8 6–7 7–9 6–8	8–9 7–9 6–7 8–9	11–2 11–2 11–2 11–2		5–7 5–6:30 5–6:30 5–6:30	7–8 6:30–8 6:30–8 6:30–8	North End So. End Out So. End In South End
4. 8th Ave. 3rd 5. Burnham-3rd	North Ave. & 3rd St.	6–8	8–9	11–2		5–6:40	6:40–8	North End
5. Burnham-3rd St.	Reed & National	6–8	8–9	11–2		5–6:30	6:30–8	South End
6. Oakland-Delaware	Clinton & National	6–8	8–9	11–2		5–6:30	6:30–8	South End
Oakland-Delaware	Brady & Astor	6–9		11–2		5–6:30	6:30–8	North End
7. Holton-Mitchell	Clinton & National	6–8	8–9	11–2		5–6:30	6:30–8	South End
Holton-Mitchell	E. Water & Wisconsin	6–8	8–9	11–2		5–6:40	6:40–8	North End
8. Muskego-8th St.	3rd & State	6–8	8–9	11–2		5–6:45	6:45–8	North End
Muskego-8th St.	Reed & National	6:30–8	6–6:30 8–9	11–2		5–6:30	6:30–8	South End
9. Clybourn-Wisconsin	Grand & 6th	6–7	7–9	11–2		5–6:20	6:20–8	
10. Twelfth-Wisconsin	Wells & 11th	6–8	8–9	11–2		5–6:45	6:45–8	
11. State-Wisconsin	State & 3rd	7–9	6–7	11–2		5–6:30	6:30–8	
12. Vliet-First Ave.	Reed & Greenfield	6–8	8–9	11–2		5–6:30	6:30–8	South End
Vliet-First Ave.	Third & Chestnut	6–8	8–9	11–2		5–6:30	6:30–8	North End
13. Vliet-Howell	Reed & Greenfield	6–7:45	7:45–9	11–2		5–6:30	6:30–8	South End
Vliet-Howell	Third & Chestnut	6–8:20	8:20–9	11–2		5–7	7–8	North End
14. North Ave.	North & Twelfth	7:15–7:45	6–7:15 7:45–9	11–2		5–6:30	6:30–8	

these are termed "maximum sub-period" and "minimum sub-period", respectively. This feature prevails throughout period No. 1 and Period No. 3, occurring practically at the same time for all lines (see table 1.) During Period No. 2 this characteristic is not so prominent and, on account of the comparatively small amount of travel, it was considered unnecessary to sub-divide it. Incidentally, these curves give a slight idea of the headway as it actually occurred.

TABLE II. SUMMARY OF PASSENGER DATA MUSKEGO EIGHTH STREET LINE

				Ave. No. people		Ave. No. of		Ave. No. pass. on		Ave. No. pass.	
Period	Sub-period	Place	Direction	on car	in car body	vacant seats	pass. stdg.	front vest.	rear vest.	on	off
3	5–6:45	8th & North	N(out)	55^{26}	44^{26}	—	2	5^{22}	9^{28}	2^{26}	4^{26}
3	6:45–8	"	"	32^{13}	25^{13}	17	—	3^{8}	6^{10}	2^{13}	4^{13}
3	Ave.	"	"	48^{39}	38^{39}	4	—	4^{20}	8^{33}	2^{39}	4^{39}
3	5–6:45	7th & Walnut	"	69^{28}	54^{28}	—	12	6^{27}	10^{28}	4^{28}	2^{28}
3	6:45–8	"	"	37^{9}	30^{9}	12	—	3^{7}	6^{8}	5^{9}	1^{9}
3	Ave.	"	"	61^{37}	48^{37}	—	6	5^{34}	9^{36}	5^{37}	2^{37}
3	5–6:45	7th&Chestnut	"	70^{26}	54^{26}	—	12	6^{25}	10^{26}	3^{26}	1^{26}
3	6:45–8	"	"	38^{9}	32^{9}	10	—	3^{8}	4^{9}	3^{9}	1^{9}
3	Ave.	"	"	61^{35}	48^{35}	—	6	6^{31}	9^{35}	3^{35}	1^{35}
3	5–6:45	3rd & State	"	63^{26}	52^{26}	—	10	5^{26}	7^{22}	5^{26}	0^{26}
3	6:45–8	"	"	27^{10}	24^{10}	18	—	3^{5}	4^{4}	2^{10}	1^{10}
3	Ave.	"	"	53^{36}	44^{36}	—	2	4^{31}	6^{26}	4^{36}	0^{36}
3	5–6:45	3rd & Grand	"	59^{26}	46^{26}	—	4	5^{22}	8^{23}	16^{26}	1^{26}
3	6:45–8	"	"	21^{9}	18^{9}	24	—	3^{4}	2^{8}	9^{9}	2^{9}
3	Ave.	"	"	49^{35}	39^{35}	3	—	5^{27}	7^{33}	14^{35}	1^{35}
3	5–6:30	Reed & Nat'l.	N(in)	16^{14}	15^{14}	27	—	2^{4}	2^{5}	4^{14}	1^{14}
3	6:30–8	"	"	19^{10}	15^{10}	27	—	2^{6}	4^{6}	1^{10}	1^{10}
3	Ave.	"	"	17^{24}	15^{24}	27	—	2^{10}	3^{11}	3^{24}	1^{24}
3	5–6:30	11th&Green'f	"	11^{13}	9^{13}	33	—	2^{5}	4^{2}	1^{13}	0^{13}
3	6:30–8	"	"	10^{16}	9^{16}	33	—	2^{6}	2^{5}	2^{16}	0^{16}
3	Ave.	"	"	11^{29}	9^{29}	33	—	2^{11}	2^{7}	1^{29}	0^{29}

The detailed observations were classified, compiled, and arranged according to these sub-periods as shown, for example, in Table 2. These results show an average of several observations during a sub-period at any point of observation. For the sake of a correct interpretation of the data, the number of observations upon which each average is based is shown by an exponent. These averages are plotted and form a basis for the " car demand curve ", Fig. 4, one axis of which is the number of people on the car while the other represents the line in question drawn to scale and shown as if the route were straight. Separate curves were plotted for each sub-period as well as for the entire period and arranged so the same vertical axis is common to all, but with the horizontal axis so placed that the curves could be easily compared. On account of period No. 4 being the theater period, during which the traffic is more or less local, investigation into its characteristics was confined to a general study. Practically all the characteristics of this period were found to be effective, to a general degree, in Periods No. 1, 2 and 3. For this reason it was considered that any scheme sufficient to meet the requirements of the other periods would satisfy those of Period No. 4. Hence, no further investigation was made.

The average number of people on the car for that particular period or sub-period was plotted and represents the average number of people arriving at that particular point of observation. Through this point, and parallel to the horizontal axis a line is drawn of such length as to represent the average number of people leaving the car. From the extreme left end of this another line is drawn, superimposed upon the former, of such a length as to represent the average number of people boarding the car at this point. The right end of this line then represents the average number of people on the car as it leaves the point of observation. This point was then joined by a straight line to the point representing the average number of people arriving at the next point of observation. The slope of the line joining any two points represents approximately the resultant of the various changes of load through the intervening territory.

The diagram at the left is drawn to scale and represents the class and extent of territory served by the line in question. The information upon which the classification of territory is based was obtained from the general report mentioned in previous pages and later outlined on the map, Fig. 5, after which that portion served by each line, either alone or in conjunction with other lines, was shown by the respective car-demand curve.

These car-demand curves show, at a glance, the principal characteristics of the line, the time, amount and duration of travel, origin of passengers, as well as their destination; and, by reference to the "district diagram," the class of people and

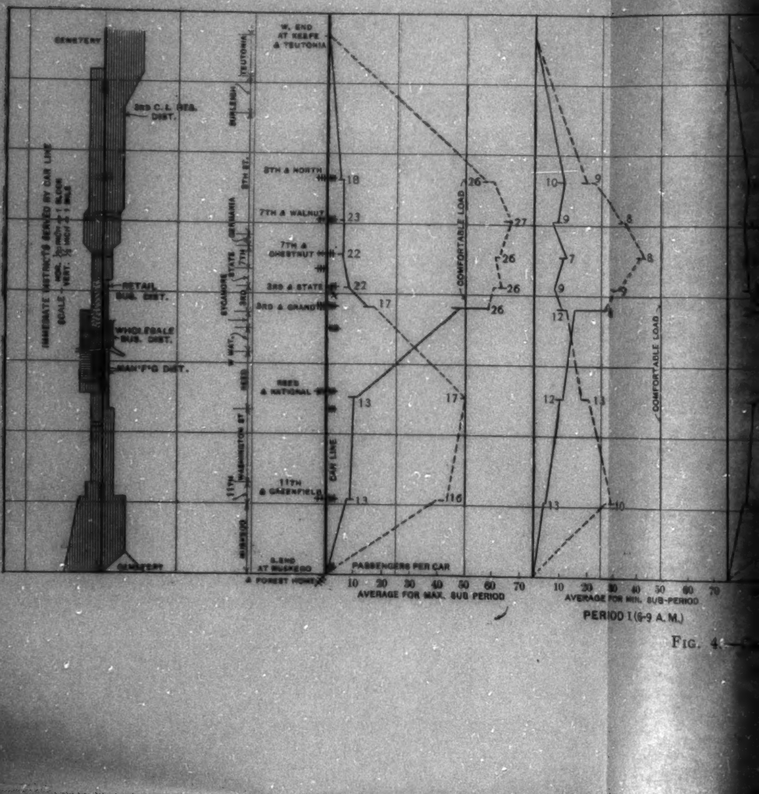
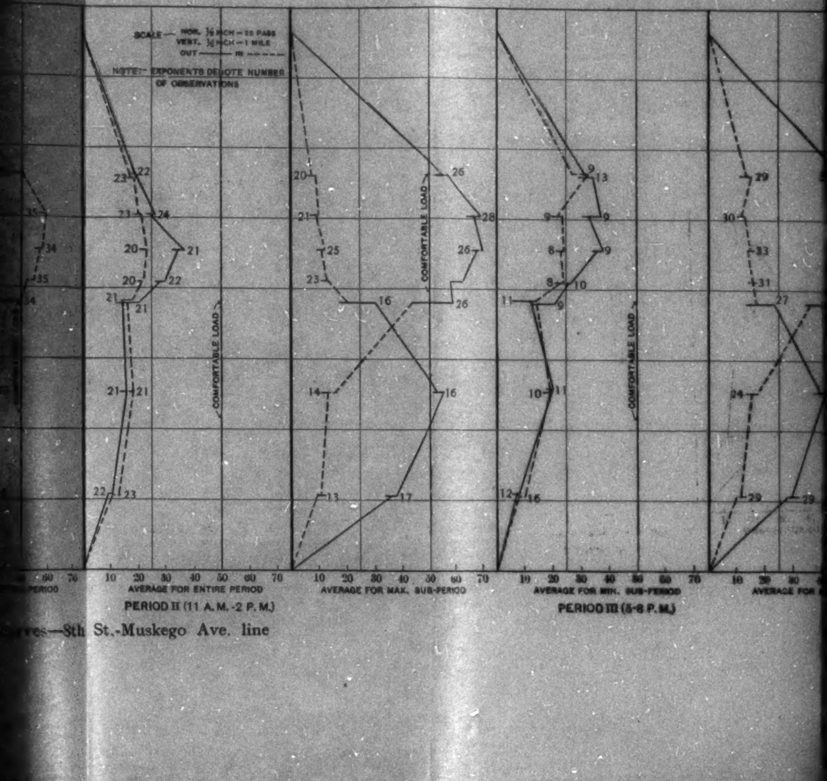

CEMETERY
3RD C. L. RES. DIST.
IMMEDIATE DISTRICTS SERVED BY CAR LINE
SCALE – HOR. 1/2 INCH = 1 BLOCK
VERT. 1/2 INCH = 1 MILE
RETAIL BUS. DIST.
WHOLESALE BUS. DIST.
MAN'F'G DIST.
CEMETERY
TEUTONIA
BURLEIGH
8TH ST.
GERMANIA
7TH
STATE
3RD
SYCAMORE
W WAT.
REED
WASHINGTON ST
11TH
MUSKEGO
W. END AT KEEFE & TEUTONIA
8TH & NORTH
7TH & WALNUT
7TH & CHESTNUT
3RD & STATE
3RD & GRAND
REED & NATIONAL
11TH & GREENFIELD
S. END AT MUSKEGO & FOREST HOME
CAR LINE
18
23
22
22
17
13
13
26
27
26
26
26
17
16
COMFORTABLE LOAD
PASSENGERS PER CAR
10 20 30 40 50 60 70
AVERAGE FOR MAX. SUB PERIOD
10
9
7
9
12
12
13
9
8
8
9
8
13
10
COMFORTABLE LOAD
10 20 30 40 50 60 70
AVERAGE FOR MIN. SUB-PERIOD
PERIOD I (6-9 A.M.)

FIG. 4



rves—8th St.-Muskego Ave. line

extent of territory served, can be seen. The average number of people boarding and leaving the car at any point of observation as well as the general tendency of the load to increase or decrease in a certain territory, is also shown. All these facts have a very material bearing upon the adequacy. A little study of the conditions, in connection with the general layout of the system, gives a definite idea as to whether or not the passengers are carried over a direct route to their destination.

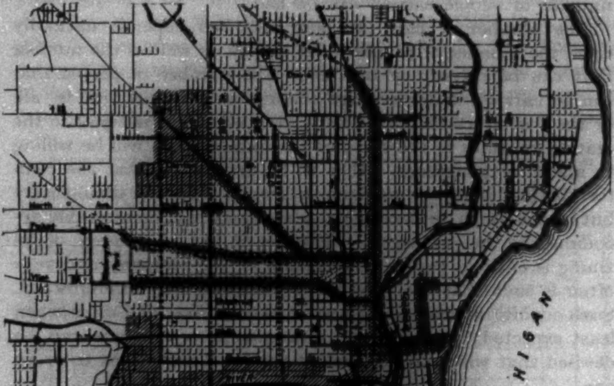

LAKE MICHIGAN
National Soldiers Home
Burnham St.
Operated Track
Non-Operated Track
Present New Track required
Future
Milwaukee N. Ry. Co
Chicago, Milw. El. Ry. Co
City-Fare Limits
Manufacturing Districts
Mercantile District
0
¼
½
¾
1 Mile

FIG. 5.—Routing of the Milwaukee Electric Railway & Light Company's lines

The adequacy, however, is not fully determined until the number of cars in service is compared with the demand for cars. By associating the curve with the number of observations upon which the car averages are based, an idea of the average number of people carried can be had.

The number of cars per hour required depends naturally upon the number of people to be carried as well as the number that can be carried by one car. The number of people that can be carried, under average conditions, with comfort to all, or the "comfortable load" as it may be called, is equal to the seating capacity of the car plus the number that will be willing to stand by preference. It is to be understood that the comfortable load is not the maximum allowable load a car should carry but is that which, under average conditions, will comfortably accommodate the passengers. The rate of flow, so to speak, of the traffic is entirely beyond the control of the company and very often is such that the cars become unexpectedly overcrowded. Such conditions are likely to occur at any time, and often when least expected. No practical arrangement or schedule can be devised that will provide comfort under all conditions to every one.

Fig. 6 shows the result of the classification and averaging of approximately 9000 observations, and gives accurate information regarding the number of people who are willing to stand of their own accord for various degrees of loading. The horizontal axis represents the degree to which the car is loaded while the vertical axis represents the average of all observations made for any particular load. The number of observations upon which each average is based is given.

The average seating capacity of a Milwaukee city car is 42. A reference to the curve shows that eight people are willing to stand when the car is loaded with 42 people. Considering the vast number of observations made and the consistent curve obtained by plotting the averages for the different degrees of loading, it is reasonable to believe that there exists a well grounded law regarding the average proportion of a load which will be willing to stand by preference. It is reasonable to believe that eight is a consistent number for this degree of loading. Hence, the comfortable load will be 50 people. A line drawn through 50 on the horizontal axis of the car-demand curve, parallel to the vertical axis, establishes a reference line. From this it is easily seen through what territories, at what times, the direction of travel, and the amount that the line is inadequate from a service point of view. A measure of this inadequacy, during any period of maximum travel, can be readily seen by observing the average number of people who are forced to stand through the territory, multiplied by the average number of cars used, and this divided by the comfortable load. This gives the number of additional cars required. The averages referred to, however, are not necessarily arithmetical averages of the numbers shown on the curve, but are such as represents a fair figure for the particular territory when the conditions, as shown by the curve, are modified by local features and good judgment.

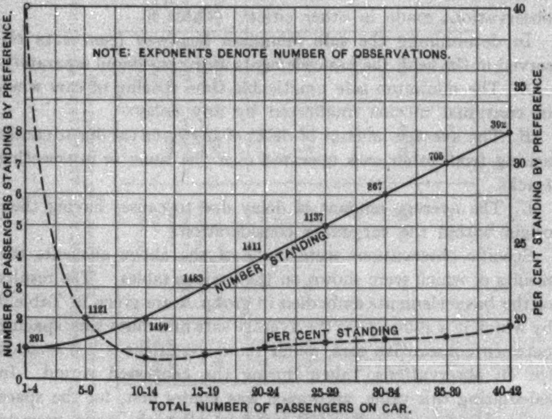


Fig. 6.—Number and percentage of passengers standing on cars by preference

The scheduled headway, or time spacing of cars, is scarcely, if ever, effective, to any degree of certainty during any great length of time, for many reasons, as for example, delay due to railroad crossings, opening of bridges, exceptionally heavy vehicular traffic, delay of other cars, slippery tracks, and other operating features that are continually fluctuating and uncertain in character. It must be considered, in the design of any schedule, that the headway should be such that with the amount of distortion which usually exists it would not be less (fewer seconds) than a certain safe minimum amount. This minimum time spacing of cars may vary for different places where a different combination of conditions is in existence. It is the determining factor that fixes the "full load" capacity of that section of track.

The following is the method used in determing the safe minimum headway at which cars can be operated on Grand Avenue near Third Street, where double tracks crossing double tracks are used in connection with one pair of opposite quadrants one more than the other. All figures are based upon accurately observed data taken in Milwaukee and compared with similar observations made in other cities. (Table 6).

In determining the safe minimum headway from data observed in the field, the basic elements were considered separately:

A. The minimum safe practicable time spacing of cars when in continual motion unaffected by any delay.

B. The average amount of delay of any given car due to causes arising from other cars operated over the same or intersecting tracks.

C. The average amount of delay due to causes having their origin within the car under consideration.

Specific observations were made of the above elements the results of which were shown on the various tables. The results of the basic elements embodied in group *A* are given in Table 3 by which it is shown that the average safe minimum time spacing between consecutive cars, under these conditions is 8.3 seconds for 49 observations, taken during the congested period. In calculating this table, allowance was made; first, for the space covered in one second at full speed to allow the train crew to act; second, for the distance required to stop the car at the observed speed with an assumed negative acceleration of 1½ miles per second; third, for a clear space of 15 feet between cars when stopped.

Group B and C Elements. Conditions which may cause delay to the movement of the cars in one direction under conditions found at Third St. and Grand Ave. are:

(*a*) Car ahead going in same direction upon approaching the intersection but taking the curve.

(*b*) A car taking curve in nearest quadrant but resulting in going in the opposite direction.

(*c*) One car crossing at right angles.

(*d*) Two cars crossing at right angles but going in opposite directions.

TABLE III. TABLE SHOWING TIME SPACING OF CARS AT THIRD STREET AND GRAND AVENUE AS AFFECTED BY GROUP A ELEMENTS

(Time of stops and intersections is not considered here)

Observations taken during	Length of car	Safe space between cars when stopped	Observed speed ft. per sec.	Miles per hour	Distance car travels after braking ft.	Safe minimum spacing ft.	No. of cars passing a given point per hr.	Headway (Time spacing of cars) seconds	Remarks
Congested period............	41′	15′	12.27	8.4	34.22	102.49	433	8.3	Average 49 observations
Non-congested period........	41	15	14.26	9.73	45.76	116.02	433	8.1	Average 36 observations
Congested period............	41	15	13.34	9.11	40.44	109.78	438	8.2	Av. frequency of cars for congested period
Congested period............	41	15	16.90	11.53	61.80	134.70	452	8.0	Frequency somewhat decreased
Congested period............	41	15	8.05	5.50	14.73	78.78	368	9.8	Much delay

(*e*) Regular service stops.

(*f*) Unusual vehicle and pedestrian traffic.

(g) Delay due to hesitancy of motorman and supervisor.

(*h*) Delay due to hesitancy of cars approaching switches before taking curves.

(*i*) Any other conditions.

Observed Data Relating to Above Conditions.

TABLE NO. IV

Date of observation	Period of traffic	Time of count	(1) Total No. of cars approaching curves	(1) Total No. of cars taking curve	Per cent $\frac{(2)}{(1)}$	Remarks
11/21/08	1	7:00–8:00 a.m.	55	17	30.9	Ordinary conditions of peak traffic
11/20/08	2	12:00–1:00 p.m.	54	16	33.8	Same as above
11/20/08	3	5:15–6:16 p.m.	91	31	34.1	Maximum conditions of peak traffic

(*a*) Since the problem resolves itself into safe operation for maximum conditions, it is advisable to use those as found in Period No. 3, or 34 per cent.

(*b*) Conditions same as (*a*), for as many cars take curve at Third St. and Grand Ave. going north as those that take curve from north going east, or 34 per cent.

(*c*) Data on cars crossing at right angles.

Date of observation	Period of traffic	Duration of count	(1) Total cars crossing going west	(2) Total cars crossing going north	(3) Total cars crossing going south	(2) + (3)	Per cent $\frac{(2)+(3)}{(1)}$
1/13/09	3	5:15 to 6:15p.m.	68	68	59	127	187*
(Congested cars taking curves not considered).							
1/11/09	Between 1&2	10:03 to 11:03a.m	39	36	35	71	182*
(Non-congested cars taking curves not considered).							

NOTE:* Relation (in per cent) of cars on two tracks to those on one intersecting track during the given interval. This percentage is here used as a measure of the tendency to interruptions.

(*d*) Two cars crossing at right angles but going in opposite directions. Approximately 10 per cent of total cars make a straight intersection.

(*e*) Regular service stop; may be made by any car (100 per cent).

(*f*) All cars are submitted to usual vehicle and pedestrian traffic (assume 10 per cent).

(*g*) Approximately 50 per cent of all cars are delayed, due to hesitancy.

(*h*) About 75 per cent of all cars taking curves are delayed on entering curves.

(*i*) Any car may be delayed approximately two seconds for other reasons.

NOTE: It should be remembered that each of the above elements (*a*) to (*i*), inclusive, relates to interruptions caused by a preceding or intersecting car.

TABLE 5. DETERMINATION OF THE COMPOSITE DELAY DUE TO GROUPS B AND C ELEMENTS
(By weighted averages)

Cause or condition	Per cent of cars affected as observed	Seconds delay	Seconds × per cent
a	34%	15.4	523.6
b	34	15.4	523.6
c	187	9.9	1851.3
d	10	13.0	130.0
e	100	15.2	1520.0
f	10	8.0	80.0
g	50	5.0	250.0
h	75	5.0	375.0
i	100	2.0	200.0
Total	600		5453.50

Weighted average delay for 1 per cent of cars observed is 9.09 seconds.

As shown in table 4 the number of cars actually observed was 91 and is represented by 100 per cent in the above table. From this the composite delay due to the causes listed under groups *B* and *C* is 9.99 seconds, or 10 seconds.

The minimum safe practicable headway is, therefore, 8.3 plus 10 seconds, or 18.3 seconds. By a comparison and interpretation of data obtained in various other similar cities (Table 6) it is considered that the operating speed in Milwaukee is somewhat faster than that of other cities. For this reason a minimum safe practicable headway of 20 seconds is more conservative. It will permit a maximum of 180 cars per hour to pass a given point in one direction with safety. A comparison of this minimum safe headway and the headway in operation on Grand Ave., near Third St.,(see Fig. 7) gives an idea as to the adequacy of this section of track. Forty-eight cars out of 197, or 25.4 per cent, were operated at a headway which, under favorable average conditions, is equal or less than the safe minimum time spacing. If there is no possible way of reducing the amount of distortion, and the same scheduled headway is required as shown by the car demand curves, then this section is inadequate for the lines. A re-routing scheme, therefore, becomes necessary. The adequacy of any section of track, from a safety point of view, can be determined in a similar way.

The average actual headway of the various lines in the down town district for periods No. 1 and 3 is approximately 6 minutes,

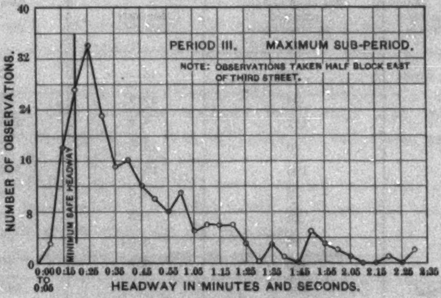


FIG. 7.—Actual conditions of headway of all cars on Grand Ave.

Fig. 8 shows the headway as observed in the down town district. Out of 6433 observations there are 4237, or 65.9 per cent less than the average headway; 890, or 13.8 per cent equal to the average headway; and 1306, or 20.3 per cent greater than the average headway.

In other words, then, 20.3 per cent of the cars, so to speak, are inconveniently spaced from a point of view of reliability. Since this amount is made up of spacings above 6 min., and range in length up to 20 min., some idea can be obtained as to the reliability characteristic of service.

As hinted before, this distortion may be due to causes which cannot be controlled but there are, however, certain environments that can be influenced with proper care on the part of the company and assistance on the part of the passengers. A very important condition effecting headway is the time required for service stops. The stop should be made at a definite point suitable for all conditions of travel thereby reducing the amount of confusion caused by passengers boarding and leaving the car. The rate at which the passengers board and leave cars, together with other minor conditions, practically determines the length of service stops. Figs. 9 and 10 show the results of an investigation made in various cities by which the fact is brought out that Milwaukee traffic is much slower than that in other cities, especially when a large number of people desire to board or leave the car. In fact the Milwaukee traveling public is practically 25 per cent slower than that found in St. Paul, Minneapolis, Duluth, Indianapolis and St. Louis. It is to be noted that practically identical curves were obtained by plotting data observed in Milwaukee on different days.

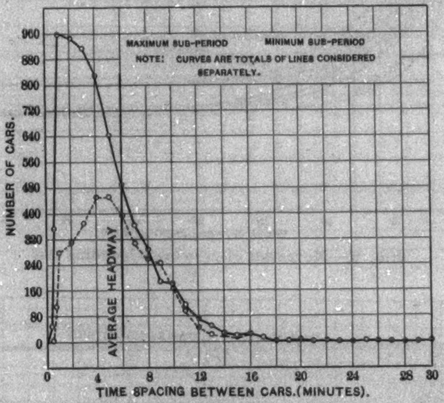


Fig. 8.—Time spacing of cars as observed at principal points—Period 1 and 3

The use of properly worded signs, etiquette on the part of the employees, as well as a little coöperation by the public, etc., are necessary to reduce the distortion of headway which results in an increase of the reliability of service.

The author has endeavored to bring out, in a very general way a method for determining the amount of service given by a railway system as well as to show an example of a method for showing the requirements of the public in a spe-

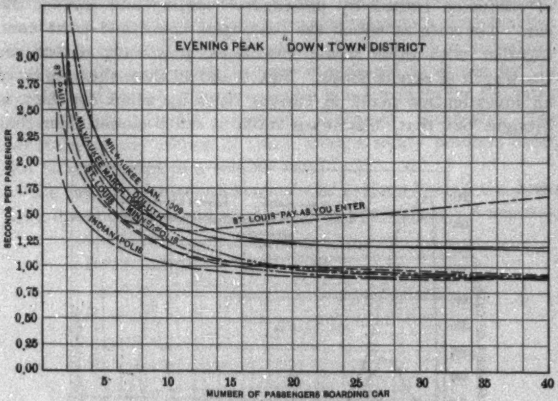


FIG. 9.—Movement of passengers boarding cars

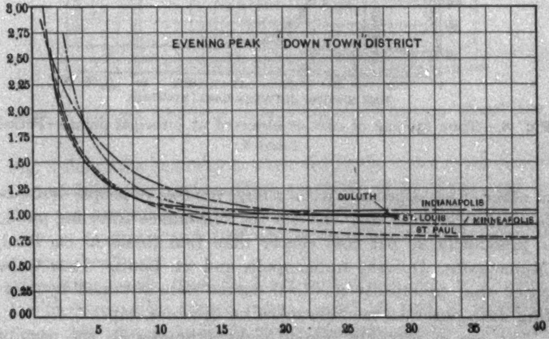
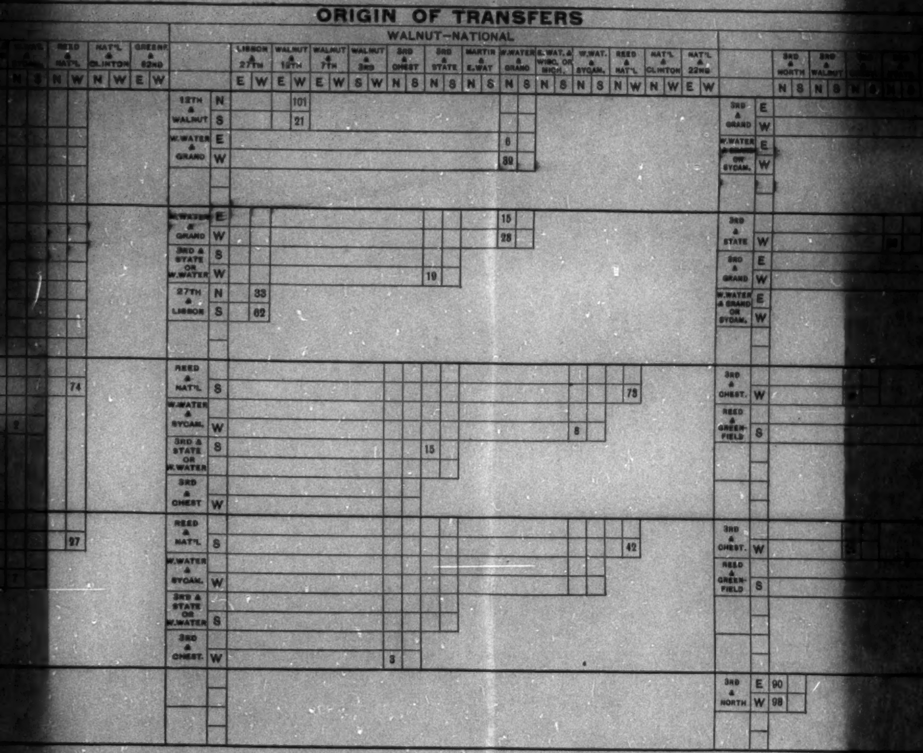


FIG. 10.—Movement of passengers leaving cars

cific case. A correct knowledge of the various conditions mentioned above is an invaluable asset to the company's operating data both with a view to satisfying the demand of the public

	WELLS-FARWELL																									
	COLLEGE & FOLSOM		FARWELL & NORTH		FARWELL & BRADY		WISC. & JACKS'N		WISC. & E. WAT.		GRAND & W. WAT. OR SYC.		GRAND & 3RD		GRAND & 6TH		WELLS & 11TH		27TH & STATE		WELLS & 35TH		WELLS & 52ND		GREENF. & 82ND	
	S	E	N	E	N	S	N	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	S	N	W
							9																			
																		60								
E							6																			
N														103												
W																										
S												3														
														22												
S														57												
W																										
S												1														
N														33												
S														14												
W				221																						
W																										

		FON DU LAC–											
		FON DU LAC & NORTH		WALNUT & 12TH		WALNUT & 7TH		WALNUT & 3RD		3RD & CHEST.		3RD & STATE	
		N	S	N	E	E	W	S	W	N	S	N	S
12TH & WALNUT	N			93									
	S			17									
W.WATER & GRAND	E												
	W												
3RD STATE OR W.WATER	S												
	W											19	
W.WATER & GRAND	E												
	W												
REED & NAT'L													
	S												
W.WATER & SYCAM.													
	W												
3RD & STATE OR W.WATER													
	S												
3RD & CHEST.													
	W									8			
REED & NAT'L													
	S												
W.WATER & SYCAM.													
	W												
3RD & STATE OR W.WATER													
	S												
3RD & CHEST.													
	W									6			
NORTH & FON DU LAC	E	27											
	W	75											


ORIGIN OF TRANSFERS
WALNUT–NATIONAL
REED & NAT'L
NAT'L & CLINTON
GREENF. & 22ND
LISBON & 27TH
WALNUT & 12TH
WALNUT & 7TH
WALNUT & 3RD
3RD & CHEST
3RD & STATE
MARTIN & E.WAT
W.WATER & GRAND
E.WAT. & WISC. OR MICH.
W.WAT. & SYCAM.
REED & NAT'L
NAT'L & CLINTON
NAT'L & 22ND
3RD & NORTH
3RD & WALNUT
12TH & WALNUT
W.WATER & GRAND
27TH & LISBON
3RD & STATE OR W.WATER
REED & NAT'L
W.WATER & SYCAM.
3RD & CHEST
3RD & GRAND
W.WATER & GRAND OR SYCAM.
3RD & STATE
REED & GREENFIELD
3RD & NORTH
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33
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73
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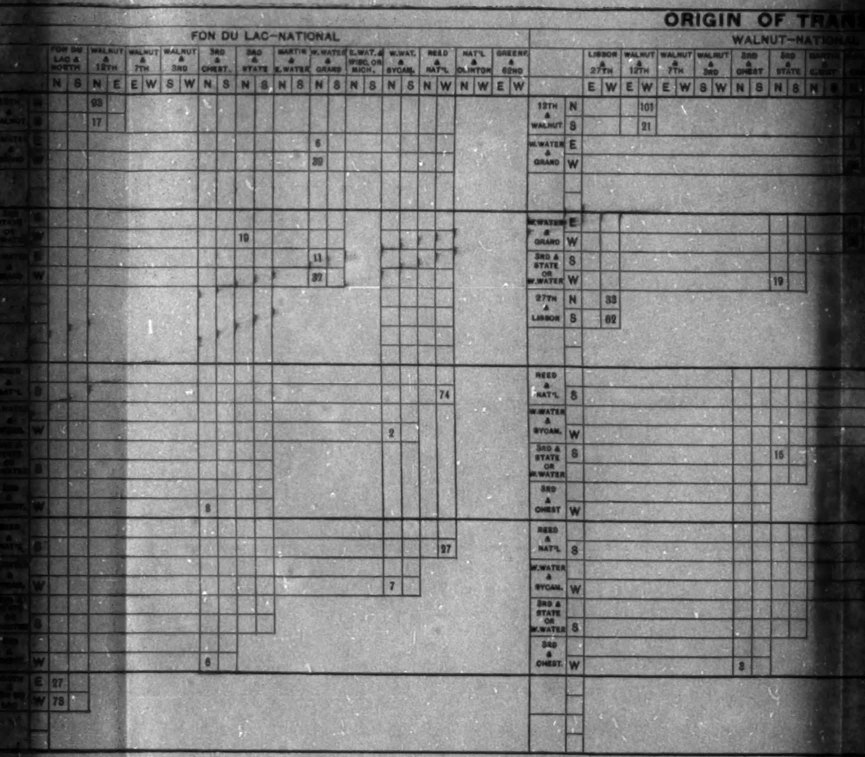
98

FIG. 11.—Diagram showing the classification of transfers used

(Transferring is from the direction indicated at the top of columns to that shown on the left margin)


ORIGIN OF TRAN
FON DU LAC–NATIONAL
WALNUT–NATIONAL
FON DU LAC & NORTH
WALNUT & 12TH
WALNUT & 7TH
WALNUT & 3RD
3RD & CHEST.
3RD & STATE
MARTIN & E.WATER
W.WATER & GRAND
E.WAT. & WISC. OR MICH.
W.WAT. & SYCAM.
REED & NAT'L
NAT'L & CLINTON
GREENF. & 62ND
LISBON & 27TH
N
S
E
W
12TH & WALNUT
W.WATER & GRAND
3RD & STATE OR W.WATER
27TH & LISBON
REED & NAT'L
W.WATER & SYCAM.
3RD & CHEST.
93
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15
2

FIG. 11.—Diagram showing the classific

(Transferring is from the direction indicated at the top of co

	REED & NAT'L		NAT'L & CLINTON		NAT'L & 22ND	
	N	W	N	W	E	W
		78				
		42				

3RD ST.–8TH AVE.

		3RD & NORTH		3RD & WALNUT		3RD & CHEST.		3RD & STATE		MARTIN & E.WAT.		3RD & GRAND		MICH. & E.WAT.		REED & NAT'L		REED & WASH.		REED & GREENF.		GREENF. & CLINTON		GREENF. & 8TH		8TH & MITCH'L	
		N	S	N	S	N	S	N	S	N	S	N	S	S	W	N	S	N	S	N	W	N	W	S	E	N	S
3RD & GRAND	E											6															
3RD & GRAND	W											27															
W.WATER & GRAND OR SYCAM.	E																										
W.WATER & GRAND OR SYCAM.	W																										
3RD & STATE	W							38																			
3RD & GRAND	E											11															
3RD & GRAND	W											7															
W.WATER & GRAND OR SYCAM.	E																										
W.WATER & GRAND OR SYCAM.	W																										
3RD & CHEST.	W					21																					
REED & GREENFIELD	S																				3						
3RD & CHEST.	W					22																					
REED & GREENFIELD	S																				8						
3RD & NORTH	E	90																									
3RD & NORTH	W	98																									

		3RD & NORTH		3RD & WALNUT		[illegible]
		N	S	N	S	N
3RD & GRAND	E					
3RD & GRAND	W					
W.WATER & GRAND OR SYCAM.	E					
W.WATER & GRAND OR SYCAM.	W					
3RD & STATE	W					
3RD & GRAND	E					
3RD & GRAND	W					
W.WATER & GRAND OR SYCAM.	E					
W.WATER & GRAND OR SYCAM.	W					
3RD & CHEST.	W					16
REED & GREENFIELD	S					
3RD & CHEST.	W					23
REED & GREENFIELD	S					
3RD & NORTH	E	78				
3RD & NORTH	W	114				

transfers used
wn on the left margin)

as well as a check on the economical features of operation and investment.

No attempt has been made to show the method of arriving at a satisfactory schedule; however, the time, direction and amount of travel are shown on the car demand curves. It has not been the object to determine what is an economical "yearly load factor" for the cars or the relation this load factor bears to the investment required. The author has made a special study of these features but on account of their importance and length of discussion involved they are not embodied in this paper. The data and description contained in the foregoing pages represents observed conditions regarding a special case where only surface lines are operated and is given with a view of bringing out a discussion that will afford many suggestions which will aid in determining the amount of service necessary to care for any given demand.

TABLE 6. DATA SHOWING AVERAGE SPEED AND TIME FOR MAKING INTERSECTIONS AS OBSERVED IN ACTUAL OPERATION IN VARIOUS CITIES

I. Speed Observations.

(a) Congested period.

	No. of observations averaged	Feet per second	Miles per hour	Remarks
Milwaukee conditions........	49	12.27	8.4	
Indianapolis "	28	13.00	8.86	
St. Louis "	7	8.65	5.9	Av. peak conditions
	1	4.6	3.1	Blocked
	4	12.45	8.5	Cars moving freely
	12	9.58	6.54	Total average
Minneapolis "	30	9.08	6.2	
St. Paul "	26	14.14	9.65	
Duluth "	31	12.51	8.53	
(*b*) Non-congested Period				
Milwaukee conditions	36	14.26	9.73	
Indianapolis "	15	16.01	10.93	
Minneapolis "	31	14.91	10.16	
St. Paul "	30	19.27	13.13	
Duluth "	30	13.40	9.13	
(*c*) Miscellaneous speed observations to show effect of a few causes of delay.				
Milwaukee conditions...........	6	13.34	9.11	Average frequency and free movement of cars
	3	16.90	11.53	Frequency decreased. Free movement of cars.
	1	8.05	5.50	Much delay.

II. Intersection and Curve Observations.

(*a*) Congested Period.

One car making a straight intersection (from the time the front end of car passes over switch frog until rear end is clear of second crossing track).

		Number of observations averaged	Seconds	
Milwaukee	conditions.............	26	9.9	
St. Louis	"	14	9.2	
Indianapolis	"	10	10.3	
Minneapolis	"................	28	10.6	
St. Paul	"	15	7.8	

Two cars making a straight intersection, but going in opposite directions (from time front end of first car blocks traffic until last car clears).

Milwaukee conditions...................		15	13.0	

Two cars taking curves of same quadrant, but going in opposite direction (from time first car enters curve until curves are cleared).

Milwaukee	conditions.............	15	18.8	
Indianapolis	"	9	12.3	

One car taking a curve (time front end of car enters curve until rear end clears curve).

Milwaukee	conditions.............	22	15.4	
St. Louis	"	6	7.2	City cars
		3	16.8	Suburban cars
Indianapolis	"	13	11.4	
Minneapolis	"	7	14.3	
St. Paul	"	14	10.8	
Duluth	"	13	8.8	

One car taking a curve with one car making an intersection resulting in both cars going in same direction (from time front end of first car blocks traffic until last car clears).

Milwaukee conditions..................		5	14.7	

(*b*) Non-congested period.

One car making a straight intersection (from the time the front end of car passes over switch frog until rear end is clear of second crossing track).

		Number of observations averaged	Seconds
Milwaukee	conditions.............	28	10.0
Minneapolis	"	21	8.4
St. Paul	"	18	7.9

One car taking a curve (time front end of car enters curve until rear end clears curve).

Milwaukee	conditions.............	14	14.2
Minneapolis	"	17	8.5
St. Paul	"	17	9.8
Duluth	"	11	8.9

III. Service Stops.

Congested period.

Period 1..............................	58	16.1
Period 2..............................	31	14.9
Period 3..............................	20	13.1
Average..................	109	15.2

A paper presented at the 27th Annual Convention of the American Institute of Electrical Engineers, Jefferson, N. H., July 1, 1910.

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SOME RECENT DEVELOPMENTS IN EXACT ALTERNATING-CURRENT MEASUREMENTS

BY CLAYTON H. SHARP AND WILLIAM W. CRAWFORD

In common with other laboratories, the Electrical Testing Laboratories have found that the more exacting demands of modern engineering work for precise alternating current measurements, have outstripped the capabilities of the older methods of measurements. It is the purpose of this paper to describe certain of the new methods and apparatus which have been developed in response to these demands.

The development of a method of measurement involves first, the establishment of certain theoretical relations between the quantity to be measured and known quantities, and second, the design of the apparatus for the application of the method. If the method together with the apparatus is such that it can be successfully applied to making accurate measurements under the conditions of ordinary engineering work, its field of usefulness is greatly extended, for it is often desirable to make tests outside the laboratory.

There are many important measurements which are outside the range of ordinary commercial instruments. Among these are the measurement of electrostatic capacities, self and mutual inductances, and of extremely large and extremely small values of voltage, current, and power. For the measurement of large quantities, the range of ordinary instruments is extended by means of voltage and current transformers, but the measurement of the ratios of the transformers presents a problem requiring special methods.

It is well recognized that zero methods furnish possibilities for precise measurements beyond the capabilities of deflecting instruments, inasmuch as the quantity to be measured is balanced against some other more easily measured quantity, and the inherent errors due to the mechanical moving parts,—springs, suspensions, divided scales, etc., of indicating instruments, are avoided. In precise direct-current work, zero methods are used to the exclusion of all others.

In alternating-current measurements, zero methods have not been used to so great an extent, largely because of the lack of proper facilities for applying them when using currents of commercial frequencies. The necessity for zero methods, is however greater in alternating-current measurements than in direct-current measurements; first, on account of the limitations of alternating-current indicating instruments, and second, because of the practical impossibility of obtaining alternating currents as steady as the direct currents furnished by the storage battery.

The difficulty of applying zero methods to alternating currents lies chiefly in the instrument used as a detector in obtaining a balance. If an electrodynamometer is used as a zero instrument, the deflection falling off as the square of the current results in low sensitiveness as the current approaches zero. By separately exciting one of the coils, the sensitiveness may be greatly increased but it is then necessary to provide means for bringing the excitation in phase with the current to be measured.

The telephone under proper conditions, is very sensitive as a zero detector. Its great advantage is its simplicity and cheapness, but when working on the commercial frequencies of 60 and 25 cycles per second, its sensitiveness is for physiological reasons, very low.

Various alternating-current galvanometers have been made, but none of them has come into wide commercial application. The vibration galvanometer when properly tuned, is very sensitive; but being a delicate suspension instrument, it is not suited to all locations, and with a change in frequency, a great decrease in sensibility occurs.

THE SYNCHRONOUS REVERSING KEY

The idea of rectifying the alternating current and passing the rectified current through a direct-current galvanometer, or detector, is not new. It underlies the secohmmeter, which has been used for many years. More recently, attempts have been made to use as a zero detector a direct current galvanometer with an ordinary brush-contact commutator on the generator shaft, or on the shaft of a synchronous motor driven by current from the same source as that to be measured. This plan has been tried and found to be capable of convenient application in many cases, but great difficulty has been found with it due to the fact that the apparent resistance of the sliding-brush contacts under working conditions tends to become very high as the current falls to a low value.

Platinum contact keys used in galvanometer circuits being known to be free from this difficulty, the next step was to construct a rectifier consisting of a reversing key with platinum contacts operated at synchronous speed by means of a synchronous motor and cam.

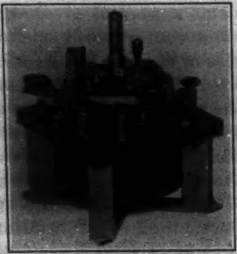

FIG. 1—Synchronous reversing key No. 1

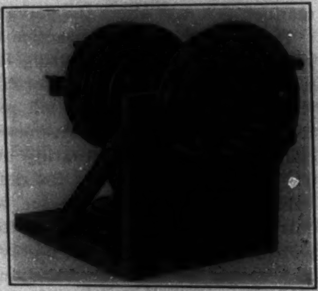

FIG. 2—Synchronous reversing key No. 2

Means are provided for adjusting the angular position of the contacts with respect to the poles of the motor, so that the reversal occurs at any desired phase of the current. By properly locating the contact setting, the galvanometer may be made to respond to any given component of the current while it is insensitive to the component in quadrature with it.

Figs. 1 and 2 shows two rectifiers which have been constructed. The first is attached to a small four-pole synchronous motor of the type described by Mr. L. T. Robinson before the last year's Convention.* This rectifier, while fairly satisfactory, had certain defects in the design of the key, and was greatly handicapped due to the impossibility of adequately insulating the key circuits from the motor circuits. Rectifier No. 2 is driven by a larger eight-pole motor which while having the disadvantage of requiring a direct-current field, has a larger torque, permitting the construction of the key with heavier moving parts and greater durability.

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* PROCEEDINGS A. I. E. E., July 1909, p. 1000.

The insulation of the motor circuits from the galvanometer circuit is of the greatest importance. An extremely small electrostatic capacity or surface leakage between them may introduce serious errors in measurement. Accordingly, in rectifier No. 2, the key was mounted on a separate bed plate insulated entirely from the motor. By grounding the bed plate of the key to the proper point in the measuring circuit, whatever residual leakage occurs may be led away in such a manner as not to affect the galvanometer.

It has been found in practice that this apparatus gives very good results. The oscillating lever and contacts will operate satisfactorily on a frequency of 60 cycles or more. The wear on the contacts is practically nil, provided that the surfaces are broad enough. The sensitiveness of the galvanometer is practically the same on alternating currents as on direct currents. Theoretically the ratio of the deflections for the same effective value of current should be the form-factor of the alternating-current wave. Due to various minor imperfections in the apparatus so far constructed, however the method is not accurate as a means for the determination of form-factors.

The apparatus places alternating-current measurements on the same basis as direct-current measurements with respect to the sensibility of the galvanometer. Using the galvanometer as a deflection instrument, such quantities as the drop in a short length of iron rail or in a bond carrying alternating current, the measurement of the leakage and charging current of a few insulators, or of a short length of cable, etc., may be easily measured The mechanical imperfections of the rectifiers so far constructed. are such that the calibration as a deflection instrument is not accurate, due to the reversal not taking place exactly at the zero of the wave, but when the calibration is made under the conditions of use, it will be sufficiently accurate for the class of measurements involved. Since the deflection obtained represents the average value of the voltage, any uncertainty in the wave form introduces a corresponding uncertainty in the calculation of the effective value. The wave form may, however, be approximately determined by taking the deflections with a series of settings of the contacts, as is explained later.

In the greater part of the work a portable galvanometer, such as a Paul single pivot galvanometer, giving one division deflection for one microampere and having 50 ohms resistance, gives sufficient sensitiveness. With a galvanometer of this type, the use of a telescope and scale is avoided, and vibration does not effect the measurements. This makes it possible to set up the apparatus in practically any location; *e.g.* in a power house, and to make measurements which with more delicate apparatus would be impracticable. An ordinary portable millivoltmeter makes a very good galvanometer for measurements not requiring the maximum sensibility.

CURRENT TRANSFORMER RATIOS

The method of introducing low resistances in the primary and secondary circuits and balancing the drops against each other by means of a zero detector, has been tried by various experimenters. The ratio of transformation is the inverse ratio of the resistances. Due to the slight phase difference between the two currents, there will remain, when the drops are adjusted to equality, a slight voltage, practically 90 degrees in phase from the resistance drops. The effect of this voltage may be eliminated by properly setting the angular position of the contacts, but unless the phase angle of the transformer is very small, it is difficult to set the contacts with sufficient accuracy.

In order to obtain a more accurate value of the ratio and at the same time to measure the phase angle, some means of bringing the two drops in phase is needed. Several methods of doing this which have been developed at the Electrical Testing Laboratories were described before last year's Convention.* The one finally adopted as most desirable is shown in Fig. 3. The primary and secondary resistances are R′ and R″, respectively. A mutual inductance, *M* is introduced which adds to the drop in R″ a small voltage, *a*, in quadrature with it, thus balancing the phase displacement. The double adjustment is made as follows:

By trial, the angular position of the contacts is found in which the galvanometer is sensitive only to changes in the secondary resistance *R″* and not to changes in the inductance. The resistance balance is made with this setting. The contacts are then shifted through 90 electrical degrees, and the inductance is adjusted until the inductive drop has been annulled. The contacts are then returned to the original position for a check on the resistance setting.

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* PROCEEDINGS A. I. E. E., Oct. 1909, p. 1356.

The ratio and phase angle are computed from the following formulæ:

$$\frac{I'}{I''} = \frac{R''}{R'}\sqrt{1+\left\{\frac{2\pi f M}{R''}\right\}^{2}}$$

$$\tan\gamma = \frac{2\pi f M}{R''}$$

When the phase angle is less than two deg. the correction term in the ratio formula may be neglected. In practice, the calculations are simplified by the use of curves which give the results directly from the readings.

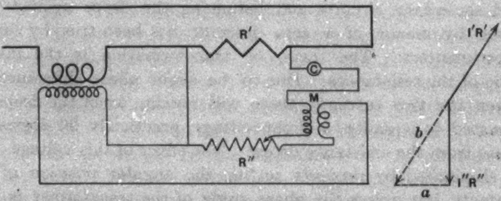


FIG. 3—Connections for ratio and phase angle test of current transformers

Sensitiveness. The minimum value of secondary resistance used is 0.025 ohm. The drop is then 0.125 volts at full load. With a portable galvanometer of the type above described the balance may theoretically be obtained within 5 microvolts in 125,000, or to one part in 25,000, by setting to 0.1 division. At 10 per cent load, a balance may be obtained within one part in 2500. The accuracy of measurement is therefore limited not by the sensitiveness of the galvanometer, but by the accuracy of calibration of the resistances, leakage and stray fields, etc. It is found that in measuring the same transformer at different times, the results will, barring mistakes, invariably agree within 0.1 per cent in ratio, and a few minutes in phase angle, at full load.

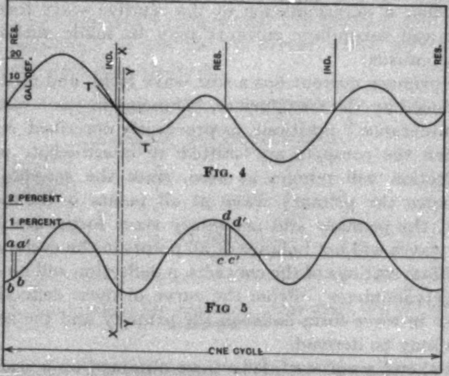
Leakage. Due to the necessity of connecting the secondary and primary circuits together, trouble is experienced from leakage and electrostatic effects. If the apparatus is at a moderate voltage above the ground, leakage may occur from the primary through the cross connection into the secondary and thence to earth. Referring to Fig. 3, it will be seen that very little of this current will pass through the galvanometer, the direct connection between R' and R'' furnishing a path of much lower resistance. The leakage current will, however, add to the current in R'' and may if large introduce an error. The amount of the leakage current is determined by removing one connection so that the total leakage must pass through the galvanometer.

Measurement of Distortion of Wave Form. An interesting property of the method is that, when used in connection with the rectifier, a determination of the relative wave form of the primary and secondary currents may be made without additional apparatus.

If the primary current has a sine wave form, and no distortion is introduced by the transformer, balancing in the " resistance " and " inductance " positions, as previously described, will insure that when the contacts are shifted to intermediate positions, the deflection will remain at zero, since the secondary wave will balance the primary wave at all points in the cycle. If, however, the primary and secondary wave forms are different, the two waves will not balance at all points in the cycle, and with intermediate settings of the contacts, a deflection will be obtained on the galvanometer. From the curve of these deflections, the difference in wave form between the primary and the secondary currents may be derived.

Fig. 4 shows a curve of deflections obtained on a transformer which on account of certain features of design showed an unusually large distortion. The test was made under severe conditions of load in order to magnify the effect. Fig. 5 shows the wave form, as derived from the above curve, of the distortion introduced into the secondary current. Evidently, the triple frequency component is predominant. The maximum ordinate is about 1.5 per cent of the secondary current. The method of derivation is as follows:

Since the rectifier closes the galvanometer circuit in one direction during a half cycle and in the reverse direction during the next half-cycle, the deflection represents the average current during a half cycle. In Fig. 5, with the contacts set to reverse at a and c, the galvanometer would be sensitive to a sine current whose maximum is at $X X$. On a distorted wave form, its deflection represents the area of the curve between $a\ b$ and $c\ d$. When the contacts are shifted to reverse at a' and c', the change in deflection represents twice the area $a\ b\ b'\ a'$, and gives a measure of the ordinate of the curve at this point. This change in deflection is equal to the difference in the ordinates at $X\ X$ and $Y\ Y$, in Fig. 4. The wave form of the distortion introduced in the secondary is therefore derived by taking the differences of successive ordinates of the observed curve of deflections, or more accurately, by taking the slopes of the observed curve at various points. Corresponding points on the observed and derived curves are 90 degrees apart.



FIGS. 4 and 5—Distortion curves of current transformer

The actual values of the ordinates of the distortion curve may be computed from the following formula:

$$x = \frac{d}{4\,d'}$$

where x = ordinate of distortion curve expressed as a percentage of the total secondary current.

d = slope of deflection curve expressed in divisions per cycle.

d' = deflection produced with the resistance setting of the contacts, by one per cent change in the secondary resistance.

Design of Apparatus. In designing apparatus for measuring current transformer ratios, an important point to be considered is the impedance introduced in the secondary circuit. Any appreciable impedance raises the voltage which must be supplied by the transformer, and thus has an influence on the ratio of transformation. In practice, transformers are often used with a single instrument of very low impedance and with very short leads, precluding the use of measuring apparatus of considerable impedance.

In the apparatus designed, the secondary resistance and primary of the mutual inductance combined amount to 0.1 ohm, and the leads introduce 0.05 ohm more, making the total 0.15 ohm. Where results are required with less resistance the small correction necessary may be easily determined by extrapolation from tests with higher values of resistance.

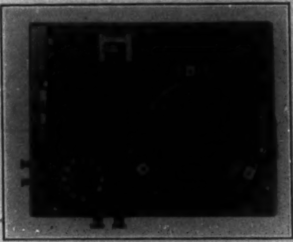


Fig. 6—Slide wire and mutual inductance

In order to save trouble in making connections, the secondary resistance and mutual inductance were constructed as a unit. The apparatus is shown in Fig. 6. A fixed resistance is used from which taps are brought out every 0.05 ohm to a dial switch. The fine adjustment is obtained by means of slide wire which shunts a part of the main resistance. The advantage of this arrangement is that sliding contacts are not introduced in the current circuit and that the amount of impedance in the secondary is always the same. The slide wire has a total resistance of 0.06 ohm, so that it overlaps the fixed steps by 0.005 ohm in either direction. This facilitates making settings near an even value. Where a number of taps are to be brought out, and where a slide wire is involved, it is difficult to make the resistance perfectly non-inductive. Loops are avoided in the leads by binding them close to the doubled manganin strip. To make the slide wire non-inductive, it is made double the required length and the unused half is brought back under the used half. The sliding contact bridges from the slide wire to a second wire lying close to it. These refinements, while they may not always be necessary, are advisable to insure accurate results in phase angle measurements.

Astatic Mutual Inductance. The mutual inductance requires careful design, the following qualities being desirable:

Long scale.
Freedom from stray field effects.
Low impedance of primary circuit.
Freedom from eddy current effects.
Permanence and reliability of calibration.
Easy adjustment.

The arrangement of coils adopted is shown in Fig. 7-a and 7-b. In Fig. 7-a, the coils are in the position of maximum mutual inductance. Rotating the hard rubber disk on which the secondary coils are mounted, through 180 degrees brings the coils to the position shown in Fig. 7-b. The lines of force from the primary coils then thread the secondary coils in a reverse direction, resulting in a negative value of mutual inductance. Between the two positions a zero is found. The positive maximum is larger than the negative maximum, which is not undesirable in the measurement of transformer ratios. Four coils being used, the inductance may be made astatic so that the effect of stray fields is small. A strong and non-uniform field may induce an error, but by keeping all instruments and heavy current conductors at a distance from the mutual inductance, or by taking direct and reversed readings, the effect may be eliminated. The primary may be constructed with a very small number of turns; the desired value of induced e.m.f. is obtained by constructing the secondary with a much larger number of turns. In order to obviate eddy currents in the primary, the coils are wound with small wire, a number of windings being placed in parallel.

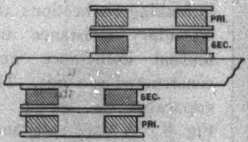


FIG. 7*a*—Position of maximum positive mutual inductance

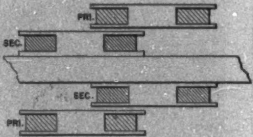


FIG. 7*b*—Position of maximum negative mutual inductance

The mechanical details are shown in Fig. 8. Due to the loca-

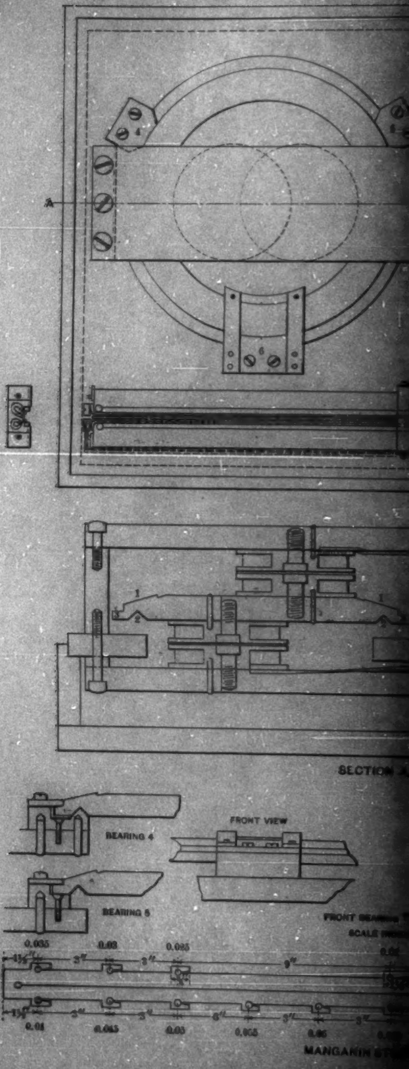
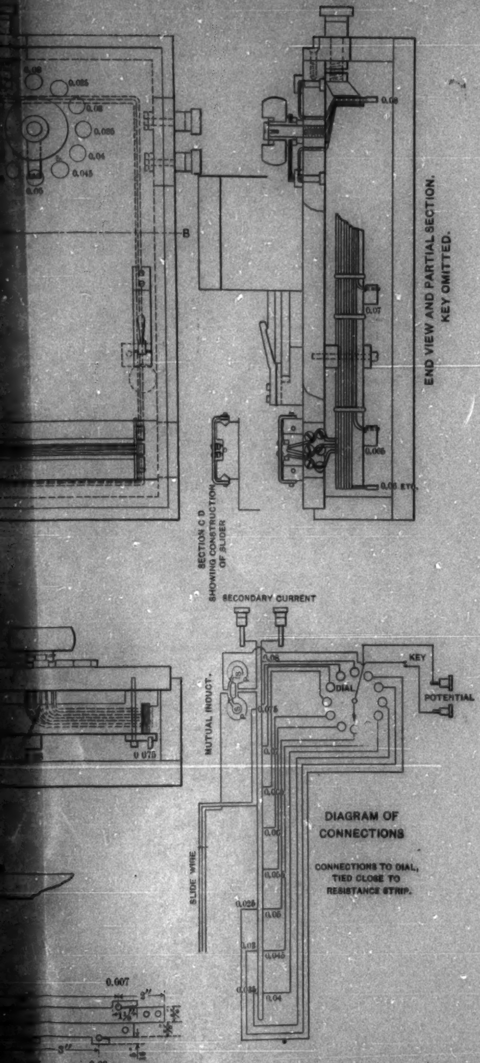

A
4
6
1
2
3
SECTION A
BEARING 4
FRONT VIEW
BEARING 5
FRONT BEARING
SCALE
0.035
0.03
0.035
1½"
2"
3"
9"
1½"
3"
3"
6"
3"
3"
0.01
0.015
0.03
0.035
0.05
MANGANIN

Fig.


0.08
0.025
0.08
0.035
0.04
0.045
0.05
B
0.08
0.07
0.035
0.05 ETC.
END VIEW AND PARTIAL SECTION.
KEY OMITTED.
SECTION C D
SHOWING CONSTRUCTION
OF SLIDER
SECONDARY CURRENT
KEY
DIAL
POTENTIAL
MUTUAL INDUCT.
0.08
0.075
0.07
0.065
0.06
0.055
0.05
0.045
0.04
0.025
0.03
0.035
SLIDE WIRE
DIAGRAM OF
CONNECTIONS
CONNECTIONS TO DIAL,
TIED CLOSE TO
RESISTANCE STRIP.
0 075
0.007
2"
1 3/4"
3"
0.08

ils of apparatus

[Sharp and Crawford 1526]

tion of the coils, it is impossible to mount the disk on a pivot, and a special three-point peripheral grooved bearing is therefore employed. The construction is satisfactory with respect to rigidity and permanency, no measurable difference having been found in calibration since the apparatus was finished. Although the bearing works stiffly, there is no great difficulty in making an exact setting.

Test Table. A set of resistance and inductance coils is provided for introduction into the secondary to duplicate the effects of various combinations of instruments. The steps are so small as to furnish practically a continuous variation.

Fig. 9 is an illustration of the entire apparatus set up for use.

Fig. 9—Complete apparatus for testing current transformers

The complete connections of the testing table are shown in Fig. 10. This table is designed with a view to the maximum convenience in laboratory use, but all measuring apparatus can be removed from it and used in any desired location.

Method using Mutual Inductances

The following additional method of measuring current transformer ratios has been considered, but has not been tried owing to the fact that the present apparatus suits the requirements. It offers, however, certain important advantages.

In the suggested method, mutual inductances are substituted for the resistances previously used. The electromotive forces induced in the secondaries are balanced against each other, one of the mutual inductances being variable. The connections are shown in Fig. 11. The phase difference is compensated by a resistance drop introduced by a slide wire, *S*, carrying the secondary current. The ratio and phase angle are given by the following formulas.

$$\text{Ratio} = \frac{M''}{M'}\sqrt{1+\tan^2\gamma}$$

$$\tan\gamma = \frac{R_s}{2\,\pi\,f\,M''}$$

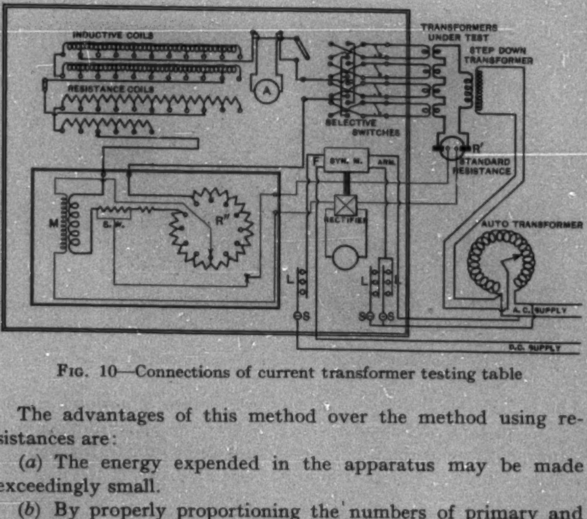

INDUCTIVE COILS
RESISTANCE COILS
A
TRANSFORMERS UNDER TEST
STEP DOWN TRANSFORMER
SELECTIVE SWITCHES
R'
STANDARD RESISTANCE
F
SYN. M.
ARM.
RECTIFIER
M
S.W.
R''
AUTO TRANSFORMER
L
L
L
S
S
S
A.C. SUPPLY
D.C. SUPPLY

FIG. 10—Connections of current transformer testing table

The advantages of this method over the method using resistances are:

(*a*) The energy expended in the apparatus may be made exceedingly small.

(*b*) By properly proportioning the numbers of primary and secondary turns on the mutual inductances, it is possible to obtain electromotive forces in the galvanometer circuit which are much greater than the drops in the primary coils hence greater sensitiveness can be obtained without the introduction of an undue impedance in the secondary of the transformer under test.

(*c*) It is not necessary to connect the primary and the secondary circuits together, and leakage effects are therefore reduced.

The disadvantages of the proposed method are:

(*a*) Mutual inductances are not so easily calibrated as resistances.

(*b*) It is difficult to construct accurate mutual inductances for large currents, although probably not more so than in the case of resistances.

(*c*) Stray field effects will influence the ratio directly, requiring astatic construction of the mutual inductances and great pains with the location of the leads carrying heavy currents.

MEASUREMENT OF MAGNETIZING CURRENTS

As a means of determining the ratio and phase angle of current transformers, where apparatus for their direct measurement is not available, or as a check on direct measurements, the value of computations from magnetizing current determinations is well recognized. Assuming a certain value of secondary current, the electromotive force which must be furnished by the transformer, and the phase relation of this electromotive force to the current, can be computed from the resistance and reactance of the secondary circuit. At the given voltage, the value of the magnetizing current and its phase relation to the voltage is determined. The primary current then includes, first, a current sufficient to make the primary ampere turns equal to the secondary ampere turns, and second, the magnetizing current which is combined with the load component in a certain phase relation which is the resultant of the phase angle between the load current and the voltage, and the phase angle between the voltage and the magnetizing current.

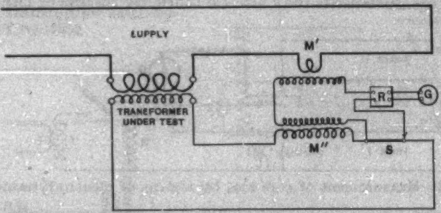


FIG 11—Measurement of current transformer ratio by means of mutual inductances

The magnetizing current is measured on open circuit the voltage being adjusted to the value corresponding to a given load of the transformer. It is best measured by supplying the current to the secondary or low current winding and computing the results in terms of the primary.

For the determination of the magnetizing current, a sensitive electrodynamometer may be used. To obtain both the magnitude and phase relation, the most obvious method is to use the electrodynamometer as an ammeter to measure the total current, and as a wattmeter to measure the power component. A preferable method is to determine the power and wattless components by separately exciting the electro-dynamometer alternately from the phases of the two-phase circuit (Fig. 12). The electrodynamometer is calibrated by substituting for the transformer a known non-inductive resistance. For very low voltages, a step-down transformer of known ratio may be introduced. The voltage is then measured on the high side and the current on the low side.

These measurements may also be made by means of the rectifier

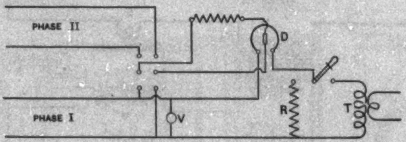


Fig. 12—Measurement of core loss by means of electrodynamometer

by inserting the transformer in an inductance bridge and ascertaining the equivalent alternating-current resistance and the reactance under the working conditions of voltage and frequency. The distortion of the wave form will have the same effect as in a ratio measurement and may be determined in the same way.

VOLTAGE TRANSFORMERS

A number of methods for measuring the ratios and phase angles of voltage transformers have been used. The simplest method is to use a rectifier; as shown in Fig. 13, R and r are high resistances connected in series to the primary circuit. A balance being obtained by varying r, the ratio of primary to secondary voltage is

$$\frac{R+r}{r}$$

As in the case of current transformer measurements, it is necessary either to pay strict attention to the setting of the contacts or to use some means of bringing the primary and secondary voltages in phase. The latter procedure is preferable. Various methods of balancing the phase displacement by introducing capacities or self or mutual inductances, may be used.

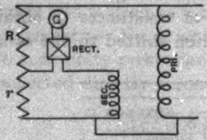
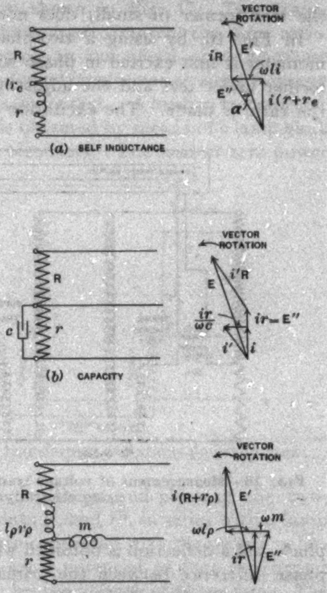

G
R
RECT.
r
SEC.
PRI.

Fig. 13—Measurement of voltage transformer ratio by means of rectifier


R
lr_e
r
VECTOR ROTATION
iR
E′
ωli
E″
a
i(r+re
R
c
r
VECTOR ROTATION
E
i′R
$\frac{ir}{\omega c}$
ir = E″
i′
i
R
$l_\rho r_\rho$
m
r
VECTOR ROTATION
i(R+rρ)
E′
ωm
ωlρ
ir
E″

(a) SELF INDUCTANCE

(b) CAPACITY

(c) MUTUAL INDUCTANCE

Fig. 14—Means of balancing phase displacement

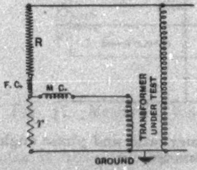

R
F. C.
M. C.
r
TRANSFORMER UNDER TEST
GROUND

Fig. 15—Measurement of voltage transformer ratio using electro-dynamometer

A few of these are illustrated in Fig. 14. The method using a mutual inductance is probably the most satisfactory.

Methods employing a sensitive electrodynamometer similar to those used in other laboratories* have been tried. It has been found possible to simplify these methods by the employment of one electrodynamometer only in phase angle tests whereas previously two electrodynamometers have been employed. The connections are shown in Figs. 15 and 16. In Fig. 15, the fine wire fixed coil of the electrodynamometer is excited by inserting it in series with the bridge resistances. The excitation being in phase with the voltage, the phase angle of the transformer (if small) does not affect the measurement.

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* L. T. Robinson, Proceedings A. I. E. E., July 1909.
Agnew & Fitch, Bulletin Bur. of Stds., Vol. 6 No. 2.

In Fig. 16, by using a two-phase circuit, the electrodynamometer is first excited in phase with the voltage of the transformer under test and the adjustment of resistances to obtain the ratio is made. The excitation is then shifted to the other phase and a deflection is obtained which is a measurement of the phase difference between the primary and secondary voltages. For the evaluation of the phase angle, the electrodynamometer is calibrated with its excitation in phase with the voltage, by altering r a small amount, r', and noting the change in deflection. Then

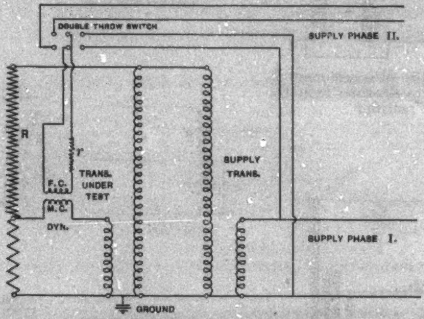

FIG. 16—Measurement of voltage transformer ratio and phase angle using electrodynamometer

$$\tan\beta = \frac{d''}{d'}\cdot\frac{r'}{r}\quad\frac{R}{R+r}$$

where d'' and d' are the deflections under test and calibration conditions respectively.

Means of Loading Transformers at Various Power Factors. In the testing of voltage transformers, it is necessary to obtain various loads at various power factors representing the equivalent of the instruments to which the transformers are to be connected in use. The method given here was devised to permit any load at any desired power factor to be obtained without the necessity of constructing a large number of inductance coils of various values. The connections are shown in Fig. 17. Two transformers are required which have approximately the same ratio. Transformer No. 2 is connected to one phase of a two-phase circuit and is used as a step-down transformer to supply energy to transformer No. 1, which is under test. A load on transformer No 1. at unity power factor is obtained by means of a lamp bank connected directly across its terminals. The load at zero power factor is obtained by introducing the second phase of the two-phase circuit between the points P, and P^1, in series with a lamp bank. If the transformers are connected with the proper polarity, these points are at the same potential so that the current flowing is determined purely by the voltage of phase two. The ammeters A_1 and A_2 respectively measure the power and wattless components of the load current, enabling their independent adjustment. The wattmeter M furnishes a check on the power factor. This method of loading is suggested as a possibility for the loading of power transformers for regulation tests, etc., at various power factors. The pumping back method could be used and the load current caused to circulate by two low voltage transformers connected to the two phases.

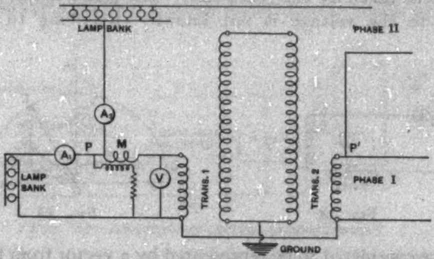

Fig. 17—Method of loading transformer at various power factors

Voltage Ratio of Current Transformers. It is often necessary when analyzing the results of current transformer tests, to know the ratio between the primary and secondary turns and it is important to be able to determine this value by test, since due to errors in manufacture, the number of turns may differ from that intended.

The ratio of turns is determined by measuring the voltage ratio in the same manner as for voltage transformers. Four or five volts is impressed on the secondary and a fraction of this is balanced against the e.m.f. induced in the primary.

To obtain the true ratio of turns, it is necessary to correct for the drop in the low-current winding due to the magnetizing current. If no magnetizing current determination has been made, an approximate value may be obtained by the following procedure. With the connections shown in Fig. 18, the milliammeter indicates the resultant of the magnetizing current and of the current taken by the voltmeter. The phase relation of this current to the voltage is not known. Referring to Fig. 19, it may be considered to be represented by a vector from the point *O*, whose end is somewhere in the arc *A B C*, which is laid out to a suitable scale. *O X* represents the voltage.

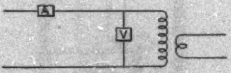

Fig. 18

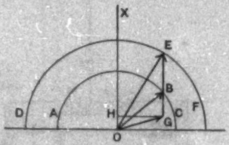

Fig. 19

A known non-inductive resistance is connected in parallel with the voltmeter and the increased current indicated by the ammeter is observed. The arc *D E F* is laid off with a radius equal to this current. The vector difference between this current and the initial current will be the current taken by the non-inductive resistance which is in phase with *O X*. Finding a point where the vertical distance between the two curves is equal to the computed value of the current in the added resistance, the points *B* and *E* are determined. *O B* is then the initial current. By subtracting from this the current taken by the voltmeter (equal to *B G*) the magnetizing current *O G* is determined. *O H* is then the component in phase with the voltage and this, together with the resistance of the winding, enables computing the correction to the observed ratio.

THE ALTERNATING-CURRENT POTENTIOMETER.

The amount of energy required by alternating-current indicating instruments prohibits their use directly in measuring very low alternating voltages. A separate circuit may, however, be obtained from the same generator and the unknown voltage measured by balancing it against a known fraction of a higher voltage which can be measured accurately by means of indicating instruments. The connections are shown in Fig. 20, in which the "standard voltage" is obtained on the line *C D*, and the unknown voltage on the line *A B*. A balance is obtained by adjusting r_1 and the phase relation. The unknown voltage is then

$$\frac{r_1}{r_1 + r_2} \text{ of the voltage on } C\,D.$$

The sensitiveness of the rectifier is sufficient to enable a voltage of a few millivolts to be measured quite accurately. The same method may be used to measure alternating currents of any desired magnitude by the use of a non-inductive shunt, and has the advantage that the necessary drop in the shunt is very small.

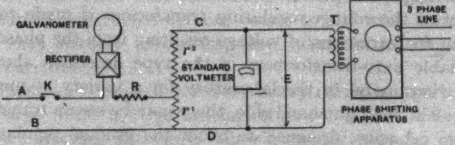

FIG. 20—Alternating current potentiometer

Methods of Adjusting Phase Relations. For obtaining a varying phase relation such as is needed in the alternating-current potentiometer arrangement, and in many other classes of tests notably test of wattmeters and watt-hour meters on low power-factors, the following methods have been found convenient. Using a three-phase circuit, (Fig. 21) a slide-wire rheostat is connected across two of the phases. The voltage circuit is obtained from the third phase and from the sliding contact on the rheostat. This arrangement furnishes a gradual shift of 60 deg. and phase relations beyond this range may be obtained by connecting the rheostat to the different phases. The method is not suited to cases where the voltage circuit draws a large amount of current and should not be used in tests on induction meters, since introducing resistance in series with the voltage circuits may cause errors. To obviate this difficulty, an apparatus using a variable auto-transformer instead of a resistance, has been devised. The variable auto-transformer consists simply of a laminated iron ring with a uniform layer of wire on it. On the outer surface of the ring, the insulation of the wire is removed making a continuous contact surface to which connection is made by means of soft carbon brushes. The connections are the same as those shown in Fig. 21. A second auto-transformer is introduced to enable the adjustment of the voltage. By means of a cam and lever arrangement, a second contact on the voltage regulating transformer is made to compensate for variations of voltage resulting from the phase shift.

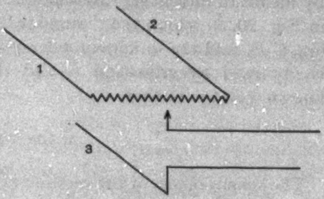

Fig. 21—Phase adjustment

Variable auto-transformers of the type described above are found very useful in the laboratory for a variety of purposes. In Fig. 9 at the right-hand side, there may be seen a transformer of large capacity, designed to effect the gradual regulation of the voltage in high-tension testing, and used in this case to regulate the primary voltage of the step-down transformer supplying current to the transformers under test. On account of the large magnetic leakage under load, indicating instruments or other apparatus susceptible to stray field effects should not be used near the transformer.

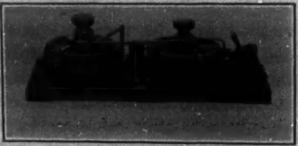

Fig. 22—Phase shifting apparatus

Measurements of Inductances, Capacities and Alternating Current Resistances

Various accurate methods of comparing inductances and capacities by means of alternating currents, using modifications of the Wheatstone bridge, are known and used. For measurements of this class, the synchronous reversing key is very serviceable. In balancing on alternating currents, a double adjustment is necessary, inasmuch as a balance must be obtained of the resistances as well as the reactances. One method of making the double adjustment is to balance the bridge on direct currents by varying the resistances, and then to balance on alternating currents by varying the inductances and capacities only. In circuits where skin effect, eddy currents, dielectric losses, iron losses, etc. are present, the equivalent resistance to alternating current is different from the resistance to direct current, and further adjustment of the resistance is necessary. As explained before, double adjustments of this character are made with great ease using the rectifier, by setting the contacts for sensitiveness either to the resistance or reactance components.

Heavy Current Non-Inductive Shunts.

The tube form of resistance has many advantages and should give practically negligible values of inductance. It has, however, been found that resistances having very low inductances can be constructed without resort to the tube form provided that suitable precautions are taken in leading in the heavy currents.

In resistances designed for very heavy currents, and to furnish a large drop, a large amount of power is to be dissipated. Designs employing flat sheets allow a greater amount of cooling surface to be obtained and sheet designs may in some cases be preferable even though more complicated in construction.

A series of resistances of the general characteristics given in the following table have been designed. Each resistance has taps brought out at ½, 1/5, 1/10, etc. of its value.

TABLE OF DATA ON RESISTANCES

Amperes	Volts	Ohms	Watts	Temperature rise, deg. cent.	Size	Weight lb.
200	2	0.01	400	15	10 in. x 9 in. cylinder	18
1000	1	0.001	1000	14.5	10 in. x 10 in. x 18 in.	80
5000	1.2	0.00024	6000	27	16 in. x 15½ in. x 18 in.	220

Only the largest will be described in detail, as its construction typifies the others and it has certain interesting properties not found in the other resistances to as marked a degree.

The construction is shown in Fig. 23. The current terminals consist of two heavy copper blocks, A and B, which lie horizontally on the top of the containing case. A series of bars, *a*, *b*, *c*, etc. are silver soldered to the terminal blocks, alternate bars being attached to the positive and negative terminals respectively. These bars extend directly downward into the oil bath. Each sheet of resistance metal is folded double and its ends attached to two adjacent bars of opposite polarity. By this arrangement, each sheet is made non-inductive, and any desired number of sheets may be connected in parallel.

In order to bring out taps at fractional values, tongues are cut in one of the sheets to which the potential binding posts are attached. The arrangement of these potential leads to avoid loops susceptible to stray fields, is equally important with the non-inductive construction of the shunt itself. A double concentric binding post is used for the potential terminals.

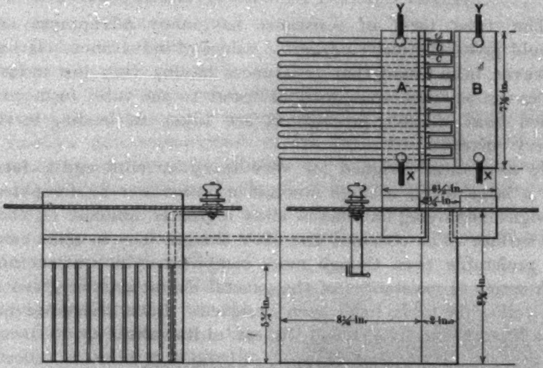

Fig. 23—5,000 ampere non-inductive shunt

The resistances are immersed in oil and cooled by a water jacket in the usual manner.

After some difficulty in determining the proper treatment for manganin sheets, pickling for 20 seconds in 50 per cent nitric acid has been found to remove the oxide and scale and give satisfactory results as regards temperature coefficient. The sheets are removed from the pickling solution, rinsed in warm water, dried in an air blast, and immediately shellacked. Before installing the insulating material and mechanical parts, the resistances are baked for 48 hours at 150 deg. cent.

Figs. 24 and 25 are photographs of the shunts assembled and taken apart, respectively.

Terminal blocks of the above described form introduce changes in resistance depending on the position of the current leads. The variations could be largely obviated by bringing out the potential taps from the middle sheet, but this is prevented by mechanical difficulties.

FIG. 24

The phase angle between the current and the potential drop also varies with the position of the leads; in the 5000 ampere resistance which has 11 resistance sheets in parallel, the phase angle at 60 cycles varied from +1 deg. to —1 deg., depending on whether the connections were placed in position *XX* or *YY*, Fig. 23. In order to remedy the variations in resistance and phase angles, a pair of extended connection plates, which may be clearly seen in Fig. 24 and 25, were installed. Using these plates

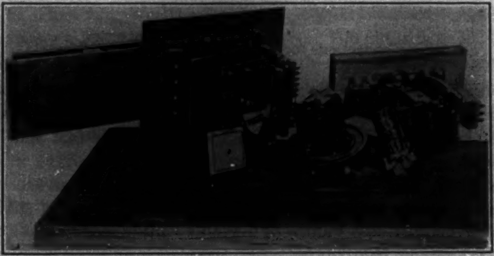

FIG. 25

no variation in phase angle was found as long as the heavy current leads did not form a large loop near the resistance.

Comparison of Inductances of Heavy Current Resistances. The measurement of the residual inductance of an approximately non-inductive resistance is dependent upon comparison with resistances which are assumed to be non-inductive. In the case of very low resistances, this comparison is difficult because the only "non-inductive" resistances whose residual inductances can safely be neglected, are those of a comparatively high value (0.1 ohm or more). However, if a sufficiently accurate method is available, a series of comparisons starting from a resistance of high value and working toward the low resistances, will enable the desired results to be obtained. The method of comparing inductances by connecting two resistances in series, exciting the fixed coil of an electrodynamometer in quadrature with the current, and transferring the moving coil from one resistance to the other, was found unsatisfactory due to the fact that the phase relation between the excitation and the current in the resistances would not remain sufficiently constant for an accurate measurement. In this connection, it may be remarked that in order to obtain with sufficient certainty the phase angle of the 0.00002 tap of the 0.0002 ohm, 5000 ampere resistance, it is necessary to have a method capable of comparing phase angles to within 0.1 to 1 minute.

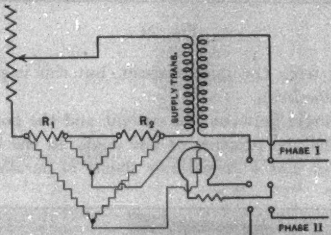

FIG. 26—Connections for measuring phase angles of shunts

The second method tried was the use of the Kelvin double bridge with two equal variable self inductances inserted in series with the bridge arms. This method was found to be so susceptible to stray field effects that without the design of special apparatus, it could not be applied in practice.

The method which was finally adopted was that shown in Fig. 26. A Kelvin double bridge is used, but no attempt is made to balance the inductive effect. A Rowland electrodynamometer with separate excitation is used as a galvanometer. The resistances of the bridge are balanced with the excitation in phase with the current in the resistances under comparison. The excitation is then placed in quadrature with the current in the resistances and the deflection is noted. This deflection is a measure of the difference in phase angle between the two resistances. The rectifier and galvanometer might be used in the same manner.

The electrodynamometer is best calibrated by observing its sensitiveness to change in resistance when the excitation is in phase with the current. The inductance of the resistance under test is then obtained from the following formula.

$$\frac{X_1}{R_1} - \frac{X_2}{R_2} = \frac{d_1}{d_2} \frac{r}{R_0}$$

where

X_1 = inductive reactance of R_1
X_2 = inductive reactance of R_2
d_1 = deflection obtained in test
d_2 = deflection obtained in calibration
r = change in variable bridge arms corresponding to deflection d_2
R_0 = resistance of one of the variable arms of the bridge.

The sensitiveness of the Rowland electrodynamometer is such that using a Kelvin double bridge having 100 ohms in each fixed arm and 100 to 1000 ohms in the variable arms, and pushing the excitation to the limit, resistances having a drop of 0.1 volt may be compared to within 20 parts of reactance in 100,000 of resistance; or in other words, within about 0.6 minute. With a larger drop, a proportionately smaller phase angle may be measured.

This method has the advantage that it is independent of steadiness of the test circuit and is free from stray field effects. It is, however, essential to take precautions against leakage effects.

It is believed that the above described methods represent at least a small advance in the art of practical alternating-current measurements and that the results obtained by them will be of value to the engineer.

DISCUSSION ON "SOME RECENT DEVELOPMENTS IN EXACT ALTERNATING CURRENT MEASUREMENTS". JEFFERSON, N. H., JULY 1, 1910.

V. Karapetoff: There are four classes of measuring instruments for measuring alternating current; the soft-iron type, of which the well-known Thomson inclined-coil ammeters represent possibly the best practice. Then the hot-wire instruments, the dynamometer type instruments, and the induction instruments, based on the principle of revolving field. All these classes of instruments are in common use, all possess certain advantages and disadvantages, but hardly any of them are adapted for precise measurements. Considerable effort has been devoted for a long time to adapt the d'Arsonval type of galvanometer, that is, an instrument consisting of a coil moving in the field of a permanent magnet, for alternating-current measurements. Dr. Sharp's instrument represents one of the possible methods of using direct-current galvanometer for alternating current measurements, namely, by rectifying the alternating current. However, there are other methods for obtaining the same end, and I wish to mention here those that I know, with a view of getting Dr. Sharp's criticisms in regard to these methods. Since he had to devise a new method, we are justified in assuming that the methods known heretofore did not possess sufficient accuracy, or for some reason were not convenient for his purpose.

The methods used so far for measuring alternating currents with direct-current precision instruments are based chiefly upon the thermal effect of alternating currents, either through a direct heating of wires, or by heating a thermo-couple. We have had before our Institute a paper by our friend Dr. Northrup on his "Comparator," an instrument devised for measuring alternating currents with great precision (TRANSACTIONS, Vol. 24, page 741). The instrument consists of two parallel wires connected by a mirror. Alternating current is sent through one wire; the heat generated expands the wire and deflects the mirror. Then direct current is sent through the other wire, so that the other wire is also expanded until the mirror returns to its first position. The direct current is measured accurately with a precision instrument, for instance a potentiometer; The effective value of the alternating current is equal to that of the direct current.

Another instrument is Professor Duddell's "Thermo-galvanometer." There you have an ordinary suspension type coil, the ends of which are connected to a thermo-couple. The alternating current to be measured is sent through a stationary heater; the heater heats the thermo-couple, and the current generated turns the moving coil; so you can calibrate the instrument with direct current, and use it to measure alternating currents. One might naturally think that this type of galvanometer is too delicate for ordinary measurements; but I lately saw it advertised in the form of a portable instrument for industrial work. Generally speaking, the disadvantage of this type of measuring instrument is that only a small and rather indefinite part of the heat generated in the alternating-current heater is transmitted to the thermo-couple.

This drawback has been recently eliminated in an instrument developed by Dr. Guggenheimer, in Germany. He ingeniously combines the alternating current and the direct current in the same circuit. The internal connections are similar to those of the Wheatstone bridge. Two opposite points of the bridge are connected to a non-inductive ammeter shunt, in the alternating current circuit. Two other points are connected to a direct-current milli-voltmeter. Four thermocouples are connected in the four branches of the bridge in such a way that they are in opposition (by pairs) with respect to the alternating current circuit, and act in parallel with regard to the direct-current circuit. In this wise, alternating currents and direct currents both flow in the same circuit, and the full extent of the heat developed by alternating currents in thermocouples contributes to the deflection of the direct-current instrument. The apparatus is made in a form similar to that of ordinary portable instruments. The Wheatstone bridge is in the base of the instrument, and the instrument, when used as an ammeter, can be provided with any number of external shunts, from one-half ampere to several thousand. The sensitiveness of the instrument is limited only by the sensitiveness of the direct-current milli-voltmeter used in it.

I should like to know what objections Dr. Sharp has to this or to any other devices used for precise alternating current measurement, and what advantage his synchronous rectifier has as compared to these?

L. T. Robinson: The necessity and the advantages of zero methods are brought out in the paper quite clearly. We all appreciate that these zero methods are always to be preferred if they do not introduce other complications that more than offset their advantages. The use of a direct current instrument as the detector is spoken of as distinguished from the use of the electro-dynamometer for the same purpose. In my experience, we have had no difficulty with the electro-dynamometer with separate excitation, and did get, as described, good results, and do now; therefore, we see no objections to it. There may be advantages in introducing the further complications, and these advantages may become more apparent as time goes on, but they are not yet fully apparent to me.

The difficulties with dynamometer instruments, due to suspensions springs, scales, etc., are also referred to, but for moderate currents, at least, we still find that this method is convenient, satisfactory and accurate, and while I still hope, as I expressed the hope a year ago, that some of the other methods would ultimately win for the work in connection with the current transformer. We still find it more satisfactory to stick to the first method which was described a year ago and which we are still using.

In connection with electro dynamometers, there are certain difficulties which come up in the measurement of very large current; I think that if these difficulties which seem to be inherent in large alternating-current precision dynamometers can be removed and they are in a fair way to be removed, the ratio determination by dynamometers will still remain a formidable competitor of more complicated methods. As far as accuracy goes, there is, I think, nothing to be desired. If we can determine the ratio and phase angle of instrument transformers with a degree of precision which is well beyond the limits of accuracy which can be had with the instruments that they are to be used with, there certainly is no use in going further. It is an unnecessary refinement, and I do not think that any one would want to use these methods of measurement for truly precision work. When we come to such work we would need to use the dynamometer instruments or other instruments which Professor Karapetoff has referred to, directly on the work. Thus, there is hardly any use in carrying the refinement in instrument transformer testing beyond a certain point. I think Dr. Sharp's improvements in the contact making key are, of course, very important and satisfactory, and such a rectifier may ultimately be the right thing to use. As I had it at first, it would do the work, but as he has improved it, it certainly does a great deal better, and to show him that I mean what I say, I have copied his device as nearly as I can and incorporated it with mine, and have used it in that form for some time. I cannot testify any more strongly to the value of the device.

I think from the statements in the paper, it is apparent that some of the things I have spoken of as difficulties with these indirect methods have come up. It is only fair to say that we have been working for some time with the method which Dr. Sharp has described - have been doing this for more than a year—and I have come in contact with some of these same difficulties myself, and also some others that are not mentioned, but I think that ultimately the method will be worked out in satisfactory shape. The author of the paper refers to obtaining of average value of alternating currents by means of these reversing commutators. I think this will ultimately be something that will be of considerable value, and in that connection I would say that I have experimented somewhat with an instrument in which the reversing commutator and other means are made use of to determine directly the average current, the root mean square current is also used in the same instrument, so that the instrument determines directly the ratio between the two, and in that way the form factor, which is an important thing in connection with transformer losses and also for several other purposes. In shifting the phase in the determination of the ratio of transformers, I think Dr. Sharp brings out quite clearly the points for which I have previously contended, that is, that it was hardly necessary in commercially good transformers to take this into account; when the phase angle is less than two degrees the correction term in the ratio formula may be neglected. Of course, it is true that we have had transformers where this phase angle is more than two degrees, but the demand for good transformers which is now well established, and which we cannot stop, and which should not be stopped, will certainly result in the production of transformers in which phase angles, like two degrees, will be unknown, and if such are offered for sale, I think they will be refused promptly.

The method of determining the distortion of wave form to which Dr. Sharp refers is most ingenious and satisfactory, and I think this will undoubtedly lead to some practical way of determining whether the wave form of a certain alternator comes within the requirements of the Institute standards or not —that is, to a short and direct way which will not involve the necessity of taking the wave with oscillograph or in some other way, to see if it comes within the requirements or not. It also seems to me that some way will be devised to handle the problem referred to, of obtaining Fig. 5 from Fig. 4, of the paper by direct measurement.

I would also emphasize the importance of being able to obtain tests of current transformers, by using a low value of impedance, in the secondary circuit. The method referred to of using mutual inductances is compared with similar methods using resistances, and then several advantages are given, but it seems to me that other methods have these same advantages, and others as well. I have not yet given up the idea that some method using thermo-couples will be the ultimate method, as no questions of wave form or phase displacement in determining the ratio can possibly modify the results. Thermal instruments have some peculiarities, and there are some difficulties in their employment, but at the same time, primarily, it is the correct principle, and I think that some means will be found ultimately so that they will be very generally employed.

In regard to the statement, "The magnetizing current is measured on open circuit the voltage being adjusted to the value corresponding to a given load of the transformer. It is best measured by supplying the current to the secondary or low current winding and computing the results in terms of the primary." This is undoubtedly true, but at the same time I am not prepared to accept this at present as the universal statement. It appears to me that this should be the correct way to do it, but at the same time, as I showed last year in my paper, in some transformers we have been able to do it and to get very exact results indeed, but I have since found that in certain other types we do not get this kind of results at all, and there is something wrong with the way we do it, or else we do not understand the situation. I am not prepared to say what it is now—I desired simply to say that this statement, while it appears that it should be true, I do not think should be accepted, without more experimental proof, as absolutely covering all cases.

In regard to the statement, " It has been found possible to simplify these methods by the employment of one electrodynamometer only, in phase angle test whereas previously two electro-dynamometers have been employed." In justice to what has been written on this subject, I revert to page 731, of the TRANSACTIONS of the Institute for 1906, where you will see the method using one dynamometer described in a discussion which I offered at that time on Mr. Curtiss's paper on Current Transformers. In fact, we have now been around the circle—I think I started with one, but finished with two, and Dr. Sharp started with two and finished with one. It is unimportant and it makes very little difference. The reason I prefer two instruments is that you can bring one instrument to zero, and have some one hold it there, and you can correct most variations in the circuit while the measurement on the second dynamometer is being made and thus determine the phase angle from one measurement. The way it is done in the paper is good, and in some cases perhaps is to be preferred. It seems to me, ordinarily viewed, it would be a little more direct to take one reading proportional to the sine of the phase angle then to take one proportional to the sine and another to the cosine, and from these readings determine the tangent.

In regard to loading transformers at various power factors, I am well satisfied with the arrangements which we have, but this, again, is a matter largely of what one can do handiest. We had plenty of reactances, and have simply taken meter parts and combined them with switches, etc.—there is little to say about the speed of using, and the convenience is about the same in either case.

The point referred to about determining the ratio of turns in current transformers, is good and could be given quite useful application. Of course, in my own work it is not often necessary to do this, as we have access to construction records, and it is only necessary to determine the ratio of turns in examining transformers of other makes.

The phase shifter illustrated in the paper I consider to be a very ingenious and satisfactory device, and I take this opportunity of complimenting the authors on the production of it.

With regard to the large current shunts, I do not approve of the construction as shown. It seems to me that they are of necessity somewhat inductive and I think a moment's consideration of the loops which are formed within these shunts, and the statement which Dr. Sharp made, that the phase angle is twenty minutes—would support this view. It is only necessary to squeeze the two sides of the circuit closer together to remove the phase angle altogether, and with it the necessity of determining what the phase angle is, and the correction for it in the measurement. This would simplify the whole matter very greatly. I have recently devised a line of shunts with these features, but which I will not describe now.

The remainder of the paper is of interest to me, but I do not think you would be particularly interested in any remarks I could offer about it. In regard to the whole paper, I want to testify to my appreciation of what has been done, and to say that it pleases me very much to note that a subject which is of real importance, although it does not directly come into the field of all of us, still the results obtained are important to all, is being considered. I feel quite sure that if this development of methods and proof of results can be continued and we can be made acquainted with the work which is done, that we will all be benefited by it.

W. H. Pratt: Allusion has been made to recent work done in directly measuring large alternating currents and large quantities of alternating current power by direct methods as opposed to the zero methods. In the first place, I have always felt doubt about the zero methods of measurement, unless we have a very close approximation to the sine wave. The distortion in the current transformer may be taken care of all right, but it is necessary to have a close approximation to the sine wave to start with.

As to these direct measurements, we have recently found it necessary to make measurements of alternating-current power and to make them with a degree of accuracy that precludes the use of current transformers.

The great source of error in alternating current instruments of large current carrying capacity has been the eddy currents induced in the massive copper conductors. Previous attempts to minimize this trouble have consisted in using stranded cable, often flattened. This procedure helps a great deal but comes far from curing the trouble.

In the twisted cable, the individual conductors are not all similarly located, and, consequently, as the cable heats, the distribution of current flow is altered.

I believe that long ago the possibility of water-cooling instruments was mentioned, but I have never seen it applied until very recently, when we constructed a water cooled watt-dynamometer of the reflected type.

In the water-cooled instrument, the trouble from uncertain current distribution is entirely taken care of. The amount of current that can be carried in the water-cooled conductor is surprisingly great. The conductor that we employed in the dynamometer, I referred to, was a copper tube 5/32 in. internal diameter and only 7/32 in. external diameter, *i.e.*, the walls of the tube are only 1/32 in. thick. City water pressure is applied at one end so as to get a heavy flow of water through the tube. Under these conditions, this very small cross section of copper will carry with about 6 deg. cent. rise a current of 1000 amperes. The flow of current could be easily doubled without causing excessive heating. At 1000 amperes, the current density in the copper is approximately 55,000 amperes per square inch.

It can be readily seen that by using a tube of the dimensions which I have just mentioned, that it is possible to make an instrument of very large current carrying capacity, having characteristics almost identical with instruments of 50 amperes capacity or thereabouts.

Of course in many places water-cooling cannot be applied, and to avoid the troubles that accompany the use of stranded cable, as ordinarily employed, we have used flat hand-braided conductors. Every individual strand is located similarly to every other strand and trouble from unequal conductivity, due to heating as well as eddy currents, are simultaneously avoided. It has been found possible to employ coils made in this way in portable instruments, obtaining thereby very high accuracy.

For some alternating current measurements, we have employed current shunts. Here again we have used direct measurements and have not stinted in the power consumed, often using, even for large currents, drops as high as 50 volts. By so doing, it is possible to proportion the apparatus so there is no question as to the relative distribution of the alternating current used in measuring and the direct current used in standardizing.

C. P. Steinmetz: There is one modification of the method of measuring alternating current which I do not see described, and which appears to me to lend itself specifically to the measurement of the mean value of extremely small alternating currents of very high frequency—frequencies beyond those where me-

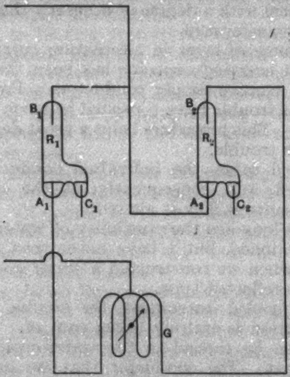

Fig. 1

chanical rectification is possible. It is by the use of an arc rectifier, as diagrammatically sketched in Fig. 1. Let R_1 and R_2 be two rectifiers, with negative terminals A_1 and A_2, positive terminals B_1 and B_2, and auxiliary terminals C_1 and C_2, and assume, as not shown here, that between A_1, C_1, and between A_2, C_2, an auxiliary direct current arc is maintained to supply the conducting vapor stream for the main arc. The incoming alternating current connects to terminals B_1 and A_2, while the rectifier terminals A_1 and B_2 connect to the two terminals of the galvanometer G, and the center of the galvanometer coil connects to the outgoing current, as shown in Fig. 1. In this case the galvanometer measures as direct current the mean value of the alternating current. The arrangement, which can be modified in various ways, is, as you see, that these two rectifiers completely rectify the successive half waves of the alternating current, irrespective of how small they are, and how high their frequency is.

Clayton H. Sharp: Mr. Karapetoff wanted to know what the criticism was of the old method and of the apparatus which is at present available. I would say to him there is not any criticism made. The purpose of the paper was not to criticise old methods, but to present something that is a modification of these older methods, or has some elements of novelty in it. I would, however, call his attention to the fact that this paper deals chiefly with zero methods, and that the instruments of which he spoke are deflection instruments, also that, being thermal instruments, they would not be well adapted to zero measurement work.

Mr. Robinson spoke of the complication of the method here presented as compared with electro-dynamometers. When electro-dynamometers are available and the work is done in the laboratory, rather than under service conditions, there is no complication in their use except that involved in any non-zero method. I maintain however that there is no complication in the method which has here been presented, and if one has not a row of electro-dynamometers, it hardly admits of question that the rectifier and direct-current galvanometer and shunts represent even less complication than is involved in the construction of the whole line of electro-dynamometers, especially as they are subject, particularly in the higher values, to difficulties of their own. Moreover shunts can be constructed for much larger currents than electro-dynamometers can be constructed for.

I want to take issue with Mr. Robinson in another matter, and that is his statement that it is unnecessary to go into the measurement of these transformers to any higher degree of refinement than the instrument which is to be used in the secondary side is capable of. I do not think he is right in that statement. I think we want to do something better than direct reading instruments will do. If our transformer is capable of better work through its constants being determined to a higher degree of accuracy, we ought to do it, and then to bring up the instrument on the secondary side to a higher standard of accuracy to correspond thereto.

As to Mr. Robinson's contention that the phase angle is a negligible quantity in determining the ratio, undoubtedly the ratio can be determined, even though the phase angle is neglected. However, the phase angle needs to be known for accurate reading with watt hour meters and wattmeters, and the method presented here includes determination of that angle without introducing any complication into the work.

L. T. Robinson: I fear Dr. Sharp misunderstood me. I appreciate the importance of the measurement of the phase angle, and brought that out in a previous paper. It was the importance of the lag—the necessity of taking into account the phase—in determining the ratio, and I would also say I fully appreciate, and described the advantages of most of the zero methods in the paper which I presented a year ago. That is not the point—it is simply the particular method of carrying out these zero methods that seems to me a little more complicated than is necessary.

Clayton H. Sharp: Regarding Mr. Robinson's reference to the paper of a year ago, I want to say that this work has been in active progress in our laboratories for well on to three years, and the method described is not a new thing with us. I described it briefly at our last convention.

William W. Crawford: I have very few points to add to what Dr. Sharp has said. In answer to Professor Karapetoff's inquiry as to the particular advantages of the rectifier, as used with the direct-current galvanometer, I would like to say that by rectifying the alternating current, the entire energy available in the galvanometer circuit can be applied to the galvanometer. A device which converts the available energy into heat, and then, by means of a thermal or some similar effect, regenerates a very small proportion of this energy into current, cannot have as great sensitiveness.

In the measurement, by deflections, of moderately large quantities, the use of a direct current instrument with a synchronous reversing key is not as accurate as the ordinary alternating current instruments.

Mr. Robinson has referred to the difficulties encountered in this method. In the article we have described in full the difficulties we have encountered in this method, such as leakage between the motor circuit and the galvanometer circuit, and imperfections in the mechanical actions of the rectifier. It has been my experience, however, that with equal sensitiveness in the electro-dynamometer and the direct-current galvanometer, the leakage effects would be nearly equal. Of course, that may be contrary to the experience of others.

Mr. Robinson has suggested an alteration in the design of the heavy capacity shunt—that designed for 5,000 amperes.

The calculated phase displacement at 60 cycles of this shunt, based on the distance between the outgoing and returning leaves of the plate, amounts to about eight minutes, whereas the measured value is twenty-two minutes. That eight minutes is the amount we could probably get rid of by squeezing the plates together. There is an amount of fourteen minutes there which is introduced by the terminal blocks, which form a considerable loop in such a manner as to affect the plates unequally. It therefore is necessary to measure the phase angle of the shunt, and I think this is a desirable precaution, even though all indications of design would point to the shunt having a zero phase displacement.

A Paper presented at the 252nd meeting of the American Institute of Electrical Engineers, New York, October 14, 1910.

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POTENTIAL STRESSES IN DIELECTRICS

BY HAROLD S. OSBORNE

HIGH VOLTAGE INSULATION

The property of a dielectric in which one is particularly interested in the design of high voltage insulation is its ability to resist the stresses exerted upon it by the voltage, tending to disrupt it, and to force a large current through the puncture.

The fundamental assumption which is made with regard to this property is that the force tending to disrupt the material at any point is measured by the electric intensity at that point, that is, by the force which would act upon a unit charge placed at that point. Thus Maxwell makes this statement:[1]

"If the electromotive intensity at any point in a dielectric is gradually increased, a limit is at length reached at which there is a sudden electrical discharge through the dielectric. The electromotive intensity when this takes place is a measure of what we may call the electric strength of the dielectric."

This critical value of the electric intensity in a dielectric is itself called, in common parlance, the electric strength of the dielectric.

Granting the existence of this definite physical constant, the electric strength of a dielectric, that is, a definite value of electric intensity which cannot be continuously or repeatedly exceeded without disrupting the dielectric, the voltage required to break down a given design of insulation depends evidently upon two factors:

1. The electric strength of the dielectric.
2. The distribution of the electric intensity, or, as one may now call it, the electric stress, in the dielectric.

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[1] *Electricity and Magnetism*, Vol. I, Art. 55.

With regard to the electric strength of the dielectric it need only be remarked that if one could devise materials of any desired electric strength, and possessing the necessary mechanical properties, insulation problems would be at an end. There seems little prospect, however, of the production of materials having greatly increased electric strengths until our knowledge of the constitution of matter is much more intimate than it is at present.

The second factor, the distribution of electric stress in the dielectric, depends upon its configuration. With an ideal distribution, the stress would be uniform throughout the dielectric, but in a homogeneous material this distribution can, unfortunately, occur only between infinite parallel conducting planes, which of course are not to be found in practice. When a conductor is insulated by surrounding it with a homogeneous dielectric, the stress is greatest at the surface of the conductor and less on the outer layers of insulation. Because of this non-uniformity in the distribution of the stress, the breakdown voltage of the wall of insulation is less than the product of its electric strength and its thickness. In high voltage insulation, the thickness of the wall required is relatively great, and the non-uniformity in the distribution of stress is so great that it becomes important to increase, by some device, the stress on the outer layers of insulation, so that they may be stressed equally with the inner layers.

In considering methods of accomplishing this result, those methods applicable to apparatus for alternating-current working are of primary importance. If one imagines the insulation to be divided into layers, it may then be considered as a set of capacities in series, the inner capacities being the smaller and hence supporting the greater stress. Two general methods are employed to equalize the stress on the layers. This equalization is accomplished either:

1. By connecting layers of metal foil, separating the layers of insulation, to points of suitable potential.
2. By increasing the capacity of the inner layers.

These same methods may be applied to apparatus for direct-current working, if it be borne in mind, in applying the second method, that in direct-current working the final stresses on the different layers are determined by their relative conductances instead of by their relative capacities.

The first method, requiring sources of various potentials, is not adapted to many cases, but can be conveniently applied in the insulation of a transformer, where any desired voltage may be tapped from the high tension winding. In England a patent[2] has been granted to the Siemens Bros. Dynamo Works, Ltd., covering this method of insulating high voltage transformers. Substantially the same expedient has been suggested[3] by Professor H. J. Ryan for protecting the minor insulation of high-voltage windings against excessive stresses.

The most obvious way of applying the second method of equalizing the stress, that of increasing the capacity of the inner layers, is to separate the layers by metal foil, and connect additional condensers across the inner layers. This method has been suggested for underground cables, but it has the disadvantage that it requires apparatus external to the cables themselves. This method has, however, been applied very ingeniously and successfully to the design of the condenser type of transformer terminal, which has been recently described[4] by Mr. A. B. Reynders in a paper presented to the American Institute of Electrical Engineers.

A method of increasing the capacity of the inner layers which is capable of a broader application, and which does not require the insertion of metallic layers, is the *grading* of the specific capacity (also called the dielectric constant) of the dielectric, making it higher in the inner layers than in the outer. This method has the advantage that it does not require the insertion of metallic layers between the layers of insulation. It is this method which is being applied in the manufacture of extra-high tension cables.

THE GRADING OF CABLES

The grading of cables seems to be worthy of a detailed consideration for three reasons:

1. The single-conductor concentric cable is of sufficiently simple configuration to permit of mathematical treatment by the ordinary methods of analysis, which lead to a complete theoretical solution of the problem of so grading the cable as to give a maximum voltage strength.

2. The manufacture of high voltage cables is now of commercial importance, and its seems certain that the demand for graded cables will increase with further development of high-voltage underground transmission.

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[2] British Patent 21860 of 1907. Engineering, July 17, 1908.

[3] *Some Elements in the Design of High Pressure Insulation.* International Electrical Congress of St. Louis, 1904.

[4] PROCEEDINGS of the American Institute of Electrical Engineers, March, 1909.

3. It is worth while for engineers, who frequently specify the thickness of insulation on their cables, to understand the possibilities offered by grading. In a rubber-insulated cable which was recently manufactured, the thickness of insulation specified by the purchasing engineer was so great that the manufacturer found it expedient to put the rubber on in two layers, though these layers were ungraded. If those layers had been properly graded, the cable could have been built with one-fourth the volume of insulation actually specified, and operated with the same maximum stresses.

Historical. The grading of cables has been discussed in several papers, the more notable of which are mentioned below.

It seems to have been first pointed out[5] to engineers by Mr. J. Swinburne, in 1897, that the electric stress in concentric cables is not uniform, but varies inversely as the distance from the axis of the cable. Mr. M. O'Gorman, in 1901, suggested[6] remedying this defect by *grading* the electrical constants of the wrappings, so that the outer layers should be stressed equally with the inner. In particular, he proposed to increase the conductivity of the inner layers of direct-current, impregnated paper cables by adding small portions of linseed oil, or of a similar oil, to the impregnating compound.

Mr. E. Jona, of Pirelli & Co., Milan, discussed the grading of cables in a classical paper[7] presented to the International Electrical Congress in 1904. Among other things, this paper describes a graded rubber-paper cable which was built by Pirelli & Co., gives the results of a theoretical investigation of the effect on the stress of stranding the conductor, and recounts some experiments made by Mr. Jona, to which frequent reference is made later in this paper.

Still more recently, Professor A. Russell has presented[8] this subject to the Institution of Electrical Engineers. Professor Russell's paper discusses methods of determining the electric strength of materials, and a number of interesting questions, such as the effect of temperature and of conductance on the distribution of the stress. In this paper are also presented formulæ for grading concentric cables, derived on the assumption that all the layers of insulation should be subjected to the same maximum and minimum stresses.

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[5] In a paper on *Electrical Transformation* before the Eng. Society. See Mr. O'Gorman's paper, Note (6).

[6] Journal of the Institution of Electrical Engineers, Vol. 30, p. 608. 1901.

[7] Transactions of the International Electrical Congress of St. Louis, 1904. Vol. II, p. 550.

[8] Journal of the Institution of Electrical Engineers. Vol. 40, p. 6. 1908.

Grading Formulæ. For heavy walls of insulation Professor Russell's formulæ do not give the best possible designs. The problem of determining the constants of a graded single-conductor cable of a given type in such proportions as to give the maximum possible voltage strength can be solved in the manner indicated below.

The electric intensity near a long, uniformly charged wire which is surrounded by concentric layers of insulation is found, by a simple integration, to be equal to

$$F = \frac{2Q}{\varepsilon \rho} \qquad (1)$$

where Q is the charge on the wire per unit length, ε is the specific capacity of the dielectric at the point considered, and ρ is the distance of that point from the axis of the wire.

If the conductor has a radius r_0. and is surrounded by a homogeneous insulation of outer radius r_n, and by a conducting sheath, the expression for the electric stress becomes

$$F = \frac{V_0}{\rho \, ln \dfrac{r_n}{r_0}} \qquad (2)$$

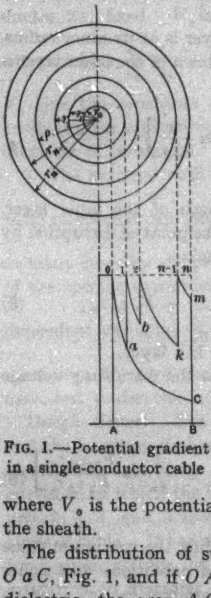

FIG. 1.—Potential gradient in a single-conductor cable

where V_0 is the potential difference between the conductor and the sheath.

The distribution of stress is then represented by the curve $O\,a\,C$, Fig. 1, and if $O\,A$ represents the electric strength of the dielectric, the area $A\,O\,a\,C\,B$ represents the highest voltage which can be impressed upon the conductor without rupturing a part, at least, of the wall of insulation. If the stress were uniform throughout the wall of insulation, the rupturing voltage would be represented by the rectangle $A\,O\,n\,B$.

If now the insulation be divided into layers having outer radii r_1, r_2, etc., and specific capacities ε_1, ε_2, etc., respectively so graded that the stress at the inside of each layer is brought up to the value *A O*, or to the electric strength of the material, the rupturing voltage of the cable is evidently represented by the area *O a* 1 *b* 2 . . . . . . *k* (*n* – 1) *m B A*, and approaches nearer and nearer to the maximum value, rectangle *A o n B*, the greater the number of layers.

In such a graded cable the equation for the stress becomes

$$F = \frac{1}{\varepsilon \rho} \cdot \frac{V_0}{\frac{1}{\varepsilon_1} ln \frac{r_1}{r_0} + \frac{1}{\varepsilon_2} ln \frac{r_2}{r_1} + . \; . \; . + \frac{1}{\varepsilon_n} ln \frac{r_n}{r_{n-1}}} \qquad (3)$$

Since the maximum stress on each layer is at its inner radius, the voltage which will just cause breakdown of the inner layer is

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_1^n \frac{1}{\varepsilon_k} ln \frac{r_k}{r_{k-1}} \right] \qquad (4)$$

where F_1 represents the electric strength of the inner layer.

If all the layers are to be stressed to the point of disruption by the same voltage, we must evidently make

$$F_1 \varepsilon_1 r_0 = F_2 \varepsilon_2 r_1 = \; . \; . \; . \; . = F_n \varepsilon_n r_{n-1} \; . \qquad (5)$$

where F_k is the electric strength of the kth layer.

Under these conditions formula (4) for the disrupting voltage is

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_1^{n-1} \frac{1}{\varepsilon_k} ln \frac{F_k \, \varepsilon_k}{F_{k+1} \, \varepsilon_{k+1}} + \frac{1}{\varepsilon_n} ln \frac{F_n \, \varepsilon_n \, r_n}{F_1 \, \varepsilon_1 \, r_0} \right] \qquad (6)$$

The problem now becomes that of finding the maximum value of V_0 in equation (6) under any given conditions and under simultaneous variation of all its variable factors. It is evident that V_0 increases indefinitely with r_n, so that quantity cannot be considered variable in obtaining a mathematical maximum. V_0 also increases indefinitely, in general, with the electric strengths. However, since these electric strengths are limited at present, in the manufacture of cables, to a very few values, they are not properly considered variable.

The specific capacities can be varied throughout a certain range, both in impregnated paper and in rubber compounds, without materially affecting the electric strength of the material.

We may then determine a mathematical maximum of V_0 for any of these conditions:

1. The outside diameter, $2\,r_n$, alone fixed. V_0 depends in this case upon the n independent variables r_0, $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_n}$ and its maximum value is the maximum voltage which can be insulated by a given external diameter of the given materials.

2. The outside diameter, $2\,r_n$, and the diameter of the conductor, $2\,r_0$, fixed. V_0 is then a function of the $(n-1)$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_n}$. The conditions for maximum V_0 give the constants of a cable which will insulate a given conductor for a given voltage with the smallest possible outside diameter of insulation.

3. The extreme radii (r_n and r_0) fixed, and also the extreme ratio of specific capacities, $\frac{\varepsilon_1}{\varepsilon_n}$. This last limitation is imposed in many cases by the present commercial limit in the variability of the specific capacities. V_0 then depends upon the $n-2$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3}, \ldots \frac{\varepsilon_1}{\varepsilon_{n-1}}$. The conditions for maximum V_0 give the same results as those for the second case, but under this added restricting condition.

Design Curves. The formulæ[9] expressing these conditions, and the resulting design formulæ for graded cables, are implicit logarithmic equations. From them, however, may be plotted curves from which the best designs may be read directly. Figures 2, 3, 4, and 5 show these design curves for four different types of cable. If one wishes to insulate a given size of conductor for a given voltage, he takes the required ratio of diameter of insulation to diameter of conductor from curve B, that ratio being read from curve A if one wishes to design for a given voltage an insulation with a given outside diameter. With a determined value of $\frac{r_n}{r_0}$ the other quantities of the design are read directly from the curves. The values of the intermediate radii of the layers are obtained by remembering that

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[9] See Appendix, Note 1.

$$F_1 \varepsilon_1 r_0 = F_2 \varepsilon_2 r_1 = \ldots\ldots = F_n \varepsilon_n r_{n-1} \qquad (5)$$

The solid line marked *Max.* gives the value of $\frac{r_n}{r_0}$ for the largest ratio of voltage to outside diameter. The vertical dot-and-dash line cuts the curves at that value of $\frac{r_n}{r_0}$ which calls for a ratio of specific capacities which seems to be the present commercial limit. For larger values of $\frac{r_n}{r_0}$ we must introduce the condition that the value of $\frac{\varepsilon_1}{\varepsilon_n}$ is kept constant at this maximum value. The design under this added condition is represented by the dotted curves, and *Max'* represents the highest ratio of voltage to outside diameter which can then be obtained.

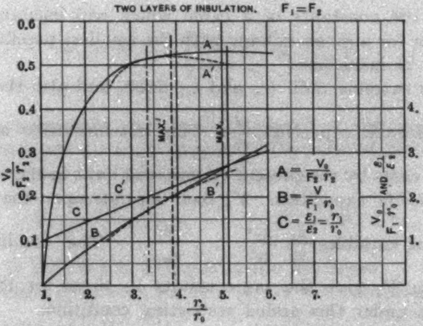

FIG. 2.—Design curves of a single-conductor cable

Figs. 2 and 4 are for cables of two layers and three layers respectively, the layers being all of the same strength. The maximum ratio of specific capacities attainable at present is taken to be two, which seems to be about correct for either rubber or impregnated paper insulations.

Figs. 3 and 5 give the curves for two-layer and three-layer cables respectively, in which the outside layer has an electric strength equal to two-thirds that of the inside layer. This is about the ratio between the electric strengths of impregnated paper and rubber, and these curves may be used for the design of cables having inside layers of rubber and an outside layer of paper. The commercial range of specific capacities for this case seems at present to be about 2.4, and curves have been drawn for this maximum value of $\frac{\varepsilon_1}{\varepsilon_n}$.

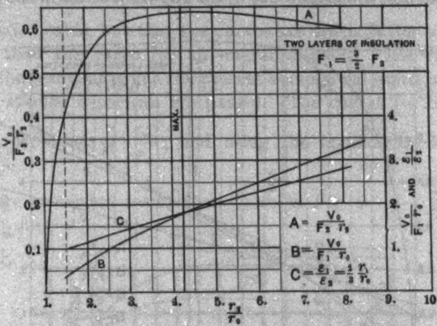

FIG. 3.—Design curves of a single-conductor cable

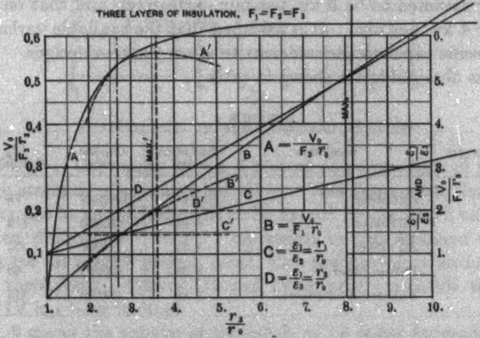

FIG. 4.—Design curves of a single conductor cable

It is interesting to note the greatest voltage which can be applied to cables of different designs having a diameter over the insulation of 70 mm. (about the largest that can be drawn, when sheathed, into a standard duct), the allowable stress in the rubber being assumed to be 6 kv. per mm. (effective), and that on the paper 4 kv. per mm. It is assumed that the available variation in specific capacities is sufficient to allow the best designs. The results obtainable are shown in table I.

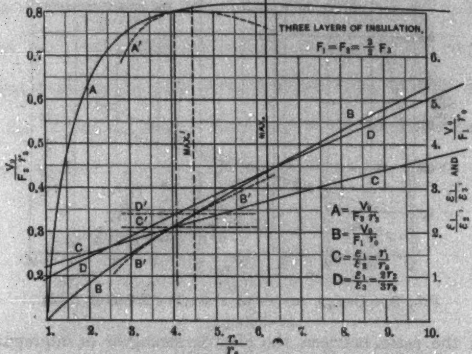

FIG. 5.—Design curves of a single-conductor cable

TABLE I

No. layers	Insulation	Rad. of core mm.	Circular mils	V_0 (kilovolts)
1	All rubber....................	12.9	1030000	78
2	All rubber....................	6.85	290000	112
3	All rubber....................	4.29	114000	132
2	Rubber-paper................	8.24	420000	90
3	Rubber-rubber-paper..........	5.59	194000	115

Fig. 6 compares what may be called the voltage efficiencies of the different designs, that is to say, the voltage sufficient to overstress a given cable is expressed as a fraction of the voltage which would puncture a uniformly stressed layer of insulation having a thickness equal to the outside radius of the insulation of the cable. The maxima are indicated by short vertical lines, and it is noticeable that the graded cables not only show maxima which are higher and at greater values of $\frac{r_n}{r_0}$ than that for the ungraded cable, but that the curves are much flatter at the maxima than the curve for an ungraded cable. The circles indicate the points at which the present commercial limits in the ratios of specific capacities are passed. The curves for cables having larger values of $\frac{r_n}{r_0}$, and using the commercial limits of $\frac{\varepsilon_1}{\varepsilon_n}$ are somewhat lower than those in Fig. 6.

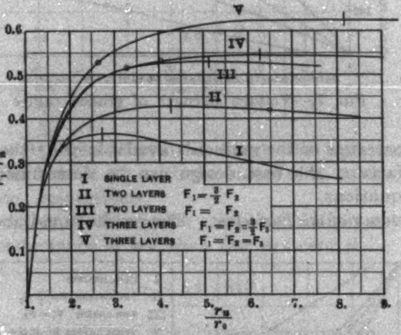

Fig. 6.—Maximum voltage efficiencies of cables

Fig. 7 gives the results of Fig. 6 plotted as percentages of the voltage strength of an ungraded cable. This figure then shows the increase in voltage strength to be gained by grading a cable of given dimensions. Curve I represents in this instance the values for an ideally graded cable, *i.e.*, one having a uniform stress throughout. Curves III and IV so nearly coincide that curve IV has been omitted.

Fig. 8 shows the volume of insulation to be saved by grading a cable of fixed voltage strength and size of conductor. The ordinates are the volumes of insulation required by graded cables expressed in per cents of the volumes required by the ungraded cable. The circles on the curves have the same significance as those in Fig. 6.

Figs. 2 to 8 are sufficient to show the results which can be obtained by the best designs under certain conditions. Formulæ can be derived from the general equations for cables of any desired types. In cases where especial conditions are imposed by the properties of the materials available or by the conditions of manufacture, the best design can be determined from the general equations.

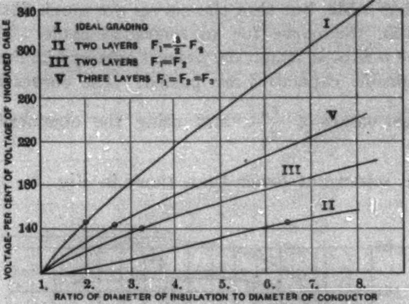

FIG. 7.—Voltage strength of graded cables

Conductance of the Dielectric. The results noted above depend on the assumption that no conductance current flows in the dielectric. This is not true, and it has been pointed out[10] by Professor Russell that the conductance may influence the distribution of stress.

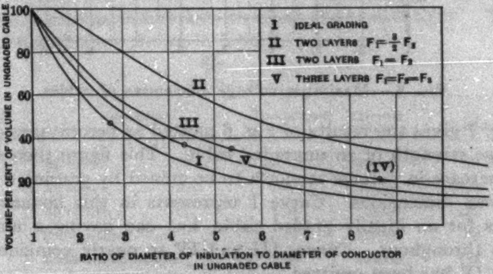

FIG. 8.—Volume of insulation in graded cables

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[10] See note (8).

If the conductance of the different layers be taken into account equation (**3**) for the stress in the dielectric becomes in complex notation

$$F = \frac{1}{\rho\left[\varepsilon - j\,\dfrac{18\,(10)^{11}\,g}{n}\right]} \cdot \frac{V_0}{\sum_1^n \dfrac{1}{\varepsilon_k - j\,\dfrac{18\,(10)^{11}\,g_k}{n}}\, ln\,\dfrac{r_k}{r_{k-1}}} \qquad (7)$$

where g_k is the conductivity of the kth layer in mhos per cm., and n is the frequency of the impressed sinusoidal electromotive force.

This equation reduces to equation (**3**) under any of the three conditions

$$\left.\begin{array}{l} n = \infty \\ g_1 = g_2 = \;.\;.\;.\;.\; = g_n = 0 \\ \dfrac{g_1}{\varepsilon_1} = \dfrac{g_2}{\varepsilon_2} = \;.\;.\;.\;.\; = \dfrac{g_n}{\varepsilon_n}\;. \end{array}\right\} \qquad (8)$$

In case $n = 0$ (direct-current working), the equation reduces exactly to the form of (3), with the values of ε_1, ε_2, etc., replaced by g_1, g_2, etc., respectively.

From equation (**7**) it may be computed that in any case the effect of conductance is less than five per cent if

$$R\,n\,\varepsilon > 5.6\,(10)^6 \qquad (9)$$

where R is the insulation resistivity in megohm-cm.

This condition, (**9**), is well met by any ordinary frequencies and insulating materials. The complete negligibility of the conductance of the dielectric in ordinary cases is well illustrated by Fig. 9, which shows the effect of low insulation resistance in the inner layer on the charging current of a particular two-layer condenser. It is seen that at commercial frequencies anything having an insulation resistivity of less than 50 megohm-cm. acts as a perfect conductor, while any resistivity greater than 40,000 megohm-cm. acts as a perfect insulator. The insulation resistivity of impregnated paper is ordinarily stated to be about 10 million megohm-cm., and that of rubber about 800 million megohms-cm.

The effect of conductivity increases with decreasing frequency, and with continuous pressures the final stresses are determined by the relative conductivities of the layers just as they are determined for alternating pressures by the specific capacities.

Temperature. Professor Russell has pointed out that the temperature gradient in the insulation may, by its effect on the conductivity, have a large influence on the distribution of stress in direct-current cables. The effect of the temperature on the specific capacities of ordinary materials is smaller, and in such a direction that it tends to reduce the stress on the inner layers of the insulation.

Multi-Conductor Cables. Cables with two and four, and particularly those with three round conductors inside a sheath are of such commercial importance that formulæ for grading them are much to be desired. Unfortunately they are like almost every other piece of electrical apparatus in that the potential gradient in the insulation cannot be exactly expressed in simple mathematical language.

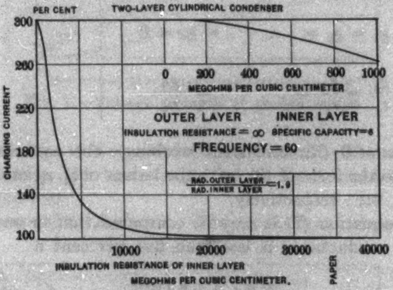

FIG. 9.—Effect of leakage conductance on charging current

A familiar approximate solution[11] is obtained by considering the charge on each conductor to be concentrated either at the centre of the conductor or at the appropriate inverse point relative to the sheath. The results obtained by such an approximation are far from exact if the conductors are large relative to the sheath. In cables for very high voltages, however, the conductors must be small relative to the sheath, and in such cases the approximation is very good. It seems probable, then, that rational grading formulæ for multi-conductor cables can be developed from the approximate solution.

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[11] See Appendix, Note 2.

CORONA IN SOLID DIELECTRICS

The theoretical results which are outlined above rest upon the fundamental assumption concerning electric strength which was mentioned at the beginning of this paper. It has been assumed that the electric strength of a dielectric is a real physical constant, measured by the electric intensity which, continuously or repeatedly applied, disrupts the dielectric. As this assumption has been assailed, notably in the discussion[12] of Professor Russell's paper, to which reference is made above, it may be worth while to consider it in some detail.

Maxwell laid a foundation for this assumption in the words already quoted: "The electromotive intensity when this (sudden electrical discharge through the dielectric) takes place is a measure of what we may call the electric strength of the dielectric."

Under certain circumstances this disruption extends through only that part of the dielectric which is near the conductors, as is the case in the familiar corona in air, and does not extend through the entire mass of insulation. Reasoning probably from the familiar and undisputed cases of corona, Professor Russell has advanced the hypothesis that there exists in solid dielectrics a corona similar to that in air, which disrupts, the entire overstressed portion uniformly, charring it and rendering it worthless as insulation.

For instance, the insulation about a wire which is insulated to more than 2.7 times its diameter will, according to this hypothesis, as the stress upon it is increased, first break down in a little uniform layer around the conductor. The breakdown of this layer will be insufficient to overstress the rest of the dielectric, so as the voltage is further increased, a zone of uniformly disrupted dielectric will extend out from the wire, within which zone the insulation is valueless, and at the surface of which the stress on the insulation is just equal to its electric strength. After this corona reaches a radius equal to 10/27th of the outside radius of the insulation, any further increase in voltage will overstress the rest of the insulation, and it will puncture.

According to this hypothesis, then, small wires insulated to a large outside diameter with a homogeneous dielectric will all be expected to puncture, irrespective of the actual size of the wire, at a voltage to be computed by replacing with a conductor all the insulation within 10/27th of the outside diameter of the insulation.

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[12] Journal of the Institution of Electrical Engineers, 1908, Vol. 40, p. 33. Professor Russell's paper and this discussion are referred to repeatedly in the following pages.

In support of this theory, Professor Russell quoted one of two careful experiments performed by Mr. Jona. He insulated two wires, one of 1 mm. diameter and one of 29 mm. diameter with the same thickness, 14 mm., of paper, and punctured the two cables thus formed. Two similar cables were made with rubber insulation. From the puncturing voltages of the larger cables can be computed the voltages at which the smaller cables should puncture according to Professor Russell's hypothesis. The results observed, and those thus computed, are given in Table II.

TABLE II

Type of insulation	Puncture voltage, Kilovolts	
	computed	observed
Paper	43	40
Rubber	31	22

The agreement in the case of the paper cable is very good. It is interesting to note that in both cases the observed values are even lower than those called for by Professor Russell's hypothesis.

Accepting this hypothesis as correct, one would expect to find a visible change in the layers of insulation which have been subject to corona. Professor Russell quoted several men who have observed the partial destruction of a wall of insulation, but it is not clear in any case that the deterioration observed can be attributed to corona. A visible change in the dielectric is, however, perhaps not a necessary result of the complete destruction of its insulating properties. Professor Russell remarked in closing the discussion of his paper:

"Whether charring occurs or not, I think that once the dielectric has been broken down, it will never prove of much future use, mechanically or electrically, as a covering."

Corona in Air. In absence of experimental proof, it appears that the idea of corona in solid dielectrics has its chief basis on the familiar occurrence of corona in gases. The present state of our knowledge of corona in air is admirably summed up by Mr. E. A. Watson in a paper[13] recently presented to the Institution of Electrical Engineers. Mr. Watson has supplemented the very complete determinations made in this country, notably by Mr. R. D. Mershon,[14] of the corona loss from wires under alternating pressures, by a very valuable series of tests with continuous pressures. His conclusions regarding the character of corona in air may be briefly summarized as follows:

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[13] *Electrician*, London, Feb. 11, 1910.

The fact that a loss does occur with direct pressures shows that it is incorrect to consider the alternating current loss to be due to the flow of charging current through the disrupted strata of air, neither can it be considered to be due to the conversion into heat of the electrostatic energy stored in the air when breakdown occurs. Experiments of Rhigi and others have shown that the discharge of electricity from steadily electrified points consists in a stream of gaseous ions moving with a velocity of about 1.5 cm. per second for a field of one volt per cm. Mr. Watson's computations, based on this fact, indicate that the discharge from the wire is carried by certain agglomerations of molecules, and not by the whole mass of air. Tests of the corona in air from different sizes of wire indicate that the electric strength of the air is not constant, but varies inversely with the diameter of the wire, dropping from a value of 81.4 kv. per cm. for a diameter of wire of 0.70 mm., to about 39 kv. per cm. for diameters of 12 mm. or larger. Mr. Watson considers the most reasonable explanation of this to be the assumption that the layers of air next to the wire have a higher electric strength than the main body of air. This is an old idea, suggested by Steinmetz, Ryan and others, and one which seems to have some experimental basis.

These ideas concerning the nature of corona in air, as summed up by Mr. Watson, are of such a nature that it may well be questioned whether there is a similar effect in solid dielectrics. The discussion of Professor Russell's paper before the Institution of Electrical Engineers produced a good deal of opposition to his views on this subject, based largely on the fact that the charring effect of partial breakdown of the dielectric does not seem to have been definitely observed. The opinion of a good many men seems to be typified by a remark of Mr. George H. Nisbett in discussing Professor Russell's paper:

" I am further strongly of the opinion that no such effect has been observed as a partial breakdown of a solid dielectric where a layer of air has been entirely absent. I have never seen anything of the sort."

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[14] PROCEEDINGS of the American Institute of Electrical Engineers, June 1908.

Mr. Jona, whose opinion on this subject is important, remarked in the same discussion:

"I have been engaged for over ten years upon this subject, and my present conclusion is that unfortunately the experiment is most difficult, and often gives results which are not in accord, owing perhaps to the non-homogeniety of the dielectrics, and that theories based solely on the gradient of the potential are deficient. Such theories are partially true, but they do not represent the whole truth."

In support of his views Mr. Jona tells of an experiment with an especial cable. A copper wire 4 mm. in diameter was insulated with jute to 8 mm., surrounded with a thin brass tape, and then with 3 mm. of rubber. With a potential of 8000 volts across this cable, the stress on the jute (3300 volts) was sufficient to puncture it, charging current flowed through to the brass tape, and the entire stress was thrown upon the rubber. This is as one would expect. A second cable was then constructed identical with the first, except that the brass tape was omitted, there being then no conducting layer between the jute and the rubber. On Professor Russell's corona hypothesis one would expect the jute to carbonize at voltages above 8000, and the capacity of the cable to increase eventually to that of the layer of rubber. As a matter of fact no such effect was observed. Mr. Jona found the capacity to be practically constant between 5000 and 15,000 volts. No carbonizing of the jute was observed. This result is distinctly not in accord with the corona hypothesis and may be due, Mr. Jona suggests, to a supporting action of some sort between the jute and the rubber.

Results similar to those of Mr. Jona's experiment have been obtained with a piece of No. 14 wire, insulated to 8.5 times its diameter with rubber. Tests of the electric strength of the rubber with which it is insulated show that at voltages higher than 35,000, the inner part of the rubber is overstressed, and hence, according to the corona hypothesis, the charging current should increase along the curve *A* of Fig. 10. As a matter of fact, it increased along curve *B*. At each point of the curve the voltage was held constant until the capacity stopped increasing. As is indicated by the double points, a slight increase with time was noted; thus at the highest point observed the charging current increased between the two values indicated in two minutes, and then was constant for five minutes. Above 44 kilovolts the cable punctured above the surface of the water in which it was immersed, at a deep gash which ozone had eaten in it. Another piece of the same cable punctured under the water at 50 kilovolts.

Experiments with Cylindrical Condensers. In the attempt to get a more definite indication of the real condition of an overstressed dielectric, a special two-layer cylindrical condenser was constructed. As indicated in Fig. 11 it consisted essentially of a heavy glass tube, or tubes, *G*, into which was drawn a rubber insulated wire, *R*. Paraffin terminal pieces, *T*, were melted onto the ends to prevent end leakage, and to prevent puncturing at the edges of the outer electrode, which consisted of tinfoil wrapped tightly about the tube and about the inner cones of the terminal pieces.

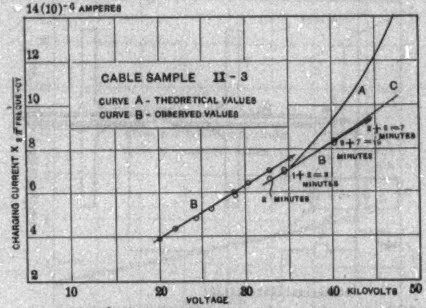

FIG. 10.—Charging Current at high voltages

The method of measuring the charging current is also indicated in Fig. 11. C_0 is a standard condenser, variable between 0.001 and 1 microfarad, connected in a series with the test condenser, *E* is an electrostatic voltmeter for measuring the voltage drop across C_0, and *P* is a protective device. This method was used not only in these experiments, but also in determining the specific capacities of the dielectrics used in the experiments. These constants were thus determined under the conditions ruling during the tests of partial breakdown.

A representative set of constants for the apparatus follows:

Rubber, $\varepsilon_1 = 6.3$ $F_1 = 18.3$

Glass, $\varepsilon_2 = 8.5$ $F_2 = 35+$

The combination therefore forms an inversely graded cylindrical condenser, in which the inner layer is overstressed by voltages which stress the outer layer but slightly.

From the constants of the apparatus it can be computed that at 24 kilovolts the rubber begins to be overstressed, and the charging current should increase, according to the corona hypothesis, along the curve *A* of Fig. 12, assuming, at 27 kilovolts the value due to the capacity of the glass cylinder alone. The curves *B*-1 and *B*-2 represent the values of charging current observed during two successive tests. It is seen that between 24 kilovolts and puncture at 28 kilovolts, the apparent capacity increased but slightly, and by no means as much as is called for by the corona hypothesis, that is, by the complete breakdown of the insulation in the overstressed region.

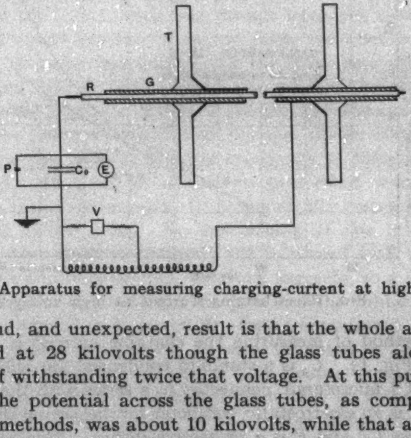

Fig. 11.—Apparatus for measuring charging-current at high voltages

A second, and unexpected, result is that the whole apparatus punctured at 28 kilovolts though the glass tubes alone were capable of withstanding twice that voltage. At this puncturing voltage the potential across the glass tubes, as computed by ordinary methods, was about 10 kilovolts, while that across the rubber was about 16 kilovolts, a little higher than the voltage (13.8 kilovolts) at which the rubber punctures alone.

A third result was obtained by withdrawing the wire from the tubes after the voltage had been applied, and examining it for insulating properties. In appearance, even under the microscope, the rubber was sound. Mechanical tests failed to indicate any deterioration. The insulation resistance of the short lengths used in the test could not be very satisfactorily tested, but it was certainly more than 100 megohms per 1000 meters. When a voltage test was applied, however, the insulation was found to be markedly deteriorated. Rubber which had been highly overstressed could not withstand at any point a voltage readable on the high-tension apparatus, and rubber which had been but slightly overstressed showed numerous very weak spots.

A difficulty in accepting these results as wholly conclusive arises from the fact that the thin layer of dielectric between the glass and the rubber, where the two did not fit exactly together, was itself disrupted by the voltage stresses. After the first tests had been made with air between the rubber and the glass an unsuccessful search was made for an insulating liquid which would not be overstressed during the experiment. Castor oil was used in some of the tests, but under the stresses exerted upon it, it evolved little bubbles of gas, even when it had been put under an air-pump directly before the experiment. A test was finally made with a mineral oil which, though it was overstressed during the experiment, showed no bubbles or visible signs of deterioration. The tests with the different insulating liquids all indicate the same results. In the tests the results of which are represented in Fig. 12 castor oil was used between the rubber and the glass.

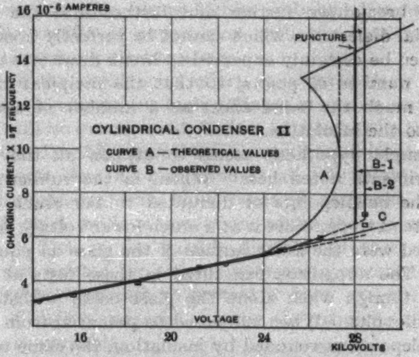

FIG. 12.—Charging current at high voltages

The possibility remains that if one could introduce between the rubber and the glass an insulating liquid which would not be overstressed during the experiment, the results noted here would not be observed. Such a possibility seems remote, however, in view of the fact that all the effects observed are explained by a very simple and convincing hypothesis concerning the nature of this partial breakdown.

Let us accept the assumption that an excessive potential gradient at any point always disrupts the dielectric at that point. It seems evident upon consideration that, even in a perfectly homogeneous dielectric, the uniform breakdown required by the Russell hypothesis would be a condition of unstable equilibrium, for if the breakdown proceeds a little farther at one point than at the points around it, the charge flowing into that advanced point will reduce the stress on the surrounding points, and the more intense field at the end of the advanced point will tend to push the breakdown farther and farther into the dielectric. Commercial dielectrics, which cannot be perfectly homogeneous, should then be certainly expected to break down not uniformly, but at a number of points, so that the incipient breakdown produces much the same effect as a number of needlepoints thrust into the insulation.

This simple hypothesis seems to explain all the results of the experiments noted here. When, in the rubber-glass condenser, the needlepoints of disrupted rubber reach the glass, they will tend to puncture it at a much lower voltage than would be required were the inner surface of the glass an equipotential surface. The apparatus punctured in these tests at about 28 kilovolts, though when alone the glass could withstand more than 50 kilovolts. When subjected to potential from an actual steel needlepoint surrounded by insulation, the same tube punctured at about 25 kilovolts. The needlepoints must push their way into the rubber in a sufficient number of places to keep the stress in the rubber down to its electric strength. They must take some additional charging current, but not nearly as much as would be required were the entire inner layer disrupted, and in a conducting condition. A general idea of the magnitude of this charging current might be obtained by considering that portion of the dielectric which would have become, according to Professor Russell's hypothesis, uniformly disrupted, to support a stress which is uniform and equal to the electric strength of the material. The charging current curves corresponding to this assumption have been drawn in Figures 10 and 12 (Curves *C*). In the test of the cable the curve so computed is in substantial agreement with the observed values. In the experiment with the rubber-glass condenser the observed values are somewhat greater than those of curve *C*, partly, perhaps, because some of the needlepoints carried charging current to little bubbles of gas in the castor oil which separated the rubber and the glass.

This idea of the needle-point character of corona in solid dielectrics explains also the results of the experiments quoted by Mr. Jona, making it easy to see how his thick insulations could puncture at voltages even lower than those called for by Professor Russell's hypothesis. It even seems probable that corona in gases is of the same general character, as this idea makes it easier to explain some of the phenomena of that corona. Therefore, though the needlepoint nature of partial breakdown in a dielectric may not be conclusively proved, the substantial accuracy of that idea seems highly probable, because it harmonizes the results of experiment with the fundamental assumption concerning electric stress.

In view of the needlepoint effect, it is particularly desirable to design an insulation for high voltages in such a way that no part of it will be overstressed, for it is apparent from the experiments reported in this paper that an overstressed insulation may be much worse than no insulation at all. It might even pay cable manufacturers who have occasion to make ungraded cables with thick walls of insulation, to fill the space within a radius of 10/27th of the outside diameter of their cables, in case it is not wanted for copper, with some material having a conductivity high enough to protect it from excessive voltage gradients, if such a material, having the requisite mechanical properties, is available.

It is desirable to have the results which have been mentioned checked with other apparatus and materials. An attempt was made to do so with a parallel plate condenser, consisting essentially of two glass plates, separated by a weaker dielectric, and separating the two electrodes, one of which was provided with an ample guard ring.

A preliminary test of the apparatus, in which air was the disrupted dielectric, gave the results shown in Fig. 13. The bend in curve I is due to the fact that, owing to irregularities in the glass plates, some air remained between them when they were pressed together. The variations of curve II from the dotted line seem to be largely due to the element of time, and it is not improbable that, were all the other variables eliminated, the voltage across the disrupted air would be found to be sensibly constant, and the current flowing through it largely a displacement current. Mr. A. W. Ewell has conducted an extensive series of tests[15] similar to this, but with plates which were vertical and open to a free supply of air. He found that for large gaps and high voltages, the voltage for a given charging current tended toward a constant value, independent of the width of the air-gap.

A condenser built with paraffin as the weaker dielectric was rejected because of the great contraction of the paraffin on solidifying. A condenser was finally built of a compound[16] which did not contract on solidifying. In testing this condenser the difficulties of insulation were found to be great, and were not surmounted in the short time which remained for the work.

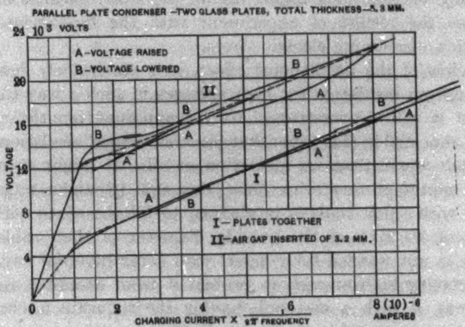

FIG. 13.—Charging current at high voltages

SUMMARY

In the design of high-voltage insulation, resort is frequently made to certain expedients which tend to equalize the stresses in the different parts of a thick wall of dielectric. In transformers metallic layers, separating layers of dielectric, are connected to points of suitable potentials. In the condenser-type of transformer terminal the capacities of the inner layers of insulation are increased by increasing their lengths; and in graded underground cables the capacities of the inner layers are increased by increasing their specific capacities.

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[15] *American Journal of Science*, November 1906.

[16] The compound consisted in 4 parts of shellac, one part of resin, and 2 parts of venice turpentine. It is recommended by Professor L. T. Moore in an article on *Dielectric Strain along the Lines of Force*, Phil. Mag., December, 1905.

Formulæ have been developed which give the best theoretical designs of graded single-conductor cables of certain given types for any given conditions. The effect of the conductivity of the dielectric is found to be entirely negligible for ordinary materials and ordinary frequencies of alternating-current working.

Results of experiment indicate that a solid dielectric, when overstressed, is not disrupted uniformly, but that the material is affected as though it had been pricked by a number of needlepoints. By this hypothesis these results, and those of earlier experiments, are explained without violating the assumption with regard to the electric strength of a dielectric which is the basis of all analytical work on the subject.

It seems probable, then, that these analytical results are based on proper assumptions; but when dealing with cases of partial breakdown, account must be taken of the true character of that breakdown.

The experiments reported in this paper were performed in the Electrical Engineering Laboratories of the Massachusetts Institute of Technology. The author wishes to acknowledge his indebtedness to the Simplex Electrical Company for samples of insulated wire, and particularly to thank Professors H. E. Clifford and Harold Pender for their assistance. Professor Clifford suggested that this investigation be undertaken, and it was commenced under his direction and completed under the direction of Professor Pender.

APPENDIX

NOTE 1. Grading formulæ for concentric cables.

$$V_0 = F_1 \varepsilon_1 r_0 \left[\sum_{1}^{n-1} \frac{1}{\varepsilon_k} \, ln \frac{F_k \varepsilon_k}{F_{k+1} \varepsilon_{k+1}} + \frac{1}{\varepsilon_n} \, ln \frac{F_n \varepsilon_n r_n}{F_1 \varepsilon_1 r_0} \right] \qquad (6)$$

A. If V_0 is a function of the $n-2$ independent variables $\frac{\varepsilon_1}{\varepsilon_2}, \frac{\varepsilon_1}{\varepsilon_3} \; . \; . \; . \; . \; \frac{\varepsilon_1}{\varepsilon_{n-1}}$, the conditions for a mathematical maximum are

$$\frac{1}{\varepsilon_k} \, ln \frac{F_k \varepsilon_k}{F_{k+1} \varepsilon_{k+1}} = \frac{1}{\varepsilon_k} - \frac{1}{\varepsilon_{k-1}} \qquad (10)$$

k having all values between and including 2 and $n-1$

B. If $\frac{\varepsilon_1}{\varepsilon_n}$ is variable, in addition to the variables of case A, the maximum of V_0 is given by the $n-2$ conditions of case A, and by the added condition

$$ln\,\frac{F_n\,\varepsilon_n\,r_n}{F_1\,\varepsilon_1\,r_0} = 1 - \frac{\varepsilon_n}{\varepsilon_{n-1}} \tag{11}$$

C. If r_0 is variable, in addition to the variables of case B, the maximum of V_0 is given by the $n-1$ conditions of case B, and by the added condition

$$ln\,\frac{F_1\,\varepsilon_1}{F_2\,\varepsilon_2} = 1. \tag{12}$$

The equations derived from these different sets of conditions for the design of graded cables of certain types follow.

I. $n = 2.\quad F_1 = F_2$

A. $V_0 = F_1\,r_0\left[\frac{\varepsilon_1}{\varepsilon_2}\,ln\,\frac{r_2}{r_0} - ln\,\frac{\varepsilon_1}{\varepsilon_2}\left(\frac{\varepsilon_1}{\varepsilon_2} - 1\right)\right]$

B. $V_0 = F_1\,r_0\left[\frac{\varepsilon_1}{\varepsilon_2} + ln\,\frac{\varepsilon_1}{\varepsilon_2} - 1\right]$

$$ln\,\frac{r_2}{r_0} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\,\frac{\varepsilon_1}{\varepsilon_2}$$

II. $n = 2.\quad F_1 = \frac{3}{2}F_2$

A. Not derived.

B. $V_0 = F_1\,r_0\left[\frac{\varepsilon_1}{\varepsilon_2} + ln\,\frac{3\,\varepsilon_1}{2\,\varepsilon_2} - 1\right]$

$$ln\,\frac{r_2}{r_0} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\,\frac{3\,\varepsilon_1}{2\,\varepsilon_2}$$

III. $n = 3.\quad F_1 = F_2 = F_3.$

A. $V_0 = F_1\,r_0\left[ln\,\frac{\varepsilon_1}{\varepsilon_2} - 1 + \frac{\varepsilon_1}{\varepsilon_2} + \frac{\varepsilon_1}{\varepsilon_3}\,ln\,\frac{\varepsilon_3\,r_3}{\varepsilon_1\,r_0}\right]$

$$ln\,\frac{\varepsilon_1}{\varepsilon_3} = 1 - \frac{\varepsilon_2}{\varepsilon_1} + ln\,\frac{\varepsilon_1}{\varepsilon_2}$$

B. $$V_0 = F_1 r_0 \left[\frac{\varepsilon_1}{\varepsilon_3} + ln \frac{\varepsilon_1}{\varepsilon_2} - 1\right]$$

$$ln \frac{r_3}{r_0} = 1 - \frac{\varepsilon_3}{\varepsilon_2} + ln \frac{\varepsilon_2}{\varepsilon_3} + ln \left[\frac{1}{1 - ln \frac{\varepsilon_2}{\varepsilon_3}}\right]$$

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{1}{1 - ln \frac{\varepsilon_2}{\varepsilon_3}}$$

IV. $n = 3$ $\quad F_1 = F_2 = \frac{3}{2} F_3$

A. $$V_0 = F_1 r_0 \left[ln \frac{\varepsilon_1}{\varepsilon_2} + \frac{\varepsilon_1}{\varepsilon_2} - 1 + \frac{\varepsilon_1}{\varepsilon_3}\, ln \frac{2}{3} \frac{\varepsilon_3}{\varepsilon_1} \frac{r_3}{r_0}\right]$$

$$l\,n \frac{3}{2} \frac{\varepsilon_1}{\varepsilon_3} = 1 - \frac{\varepsilon_1}{\varepsilon_2} + ln \frac{\varepsilon_1}{\varepsilon_2}.$$

B. $$V_0 = F_1 r_0 \left[\frac{\varepsilon_1}{\varepsilon_3} + ln \frac{\varepsilon_1}{\varepsilon_2} - 1\right]$$

$$l\,n \frac{r_3}{r_0} = 1 - \frac{\varepsilon_3}{\varepsilon_2} + ln \frac{3}{2} \frac{\varepsilon_2}{\varepsilon_3} + ln \left[\frac{1}{1 - ln \frac{3}{2} \frac{\varepsilon_2}{\varepsilon_3}}\right]$$

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{1}{1 - ln \frac{3}{2} \frac{\varepsilon_2}{\varepsilon_3}}.$$

The results of case *C* may be tabulated, and are shown in Table III.

TABLE III

Type of cable	$\frac{r_1}{r_0}$	$\frac{r_2}{r_0}$	$\frac{r_3}{r_0}$	$\frac{\varepsilon_2}{\varepsilon_1}$	$\frac{\varepsilon_3}{\varepsilon_1}$	$\frac{V_0}{F_n r_n}$
Single layer...............	2.72	—	—	—	—	0.368
I...........................	2.72	5.11	—	0.368	—	0.531
II..........................	2.72	4.25	—	0.552	—	0.640
III.........................	2.72	5.11	8.18	0.368	0.196	0.626
IV..........................	2.72	5.11	6.26	0.368	0.294	0.817
Ideal grading..............	—	—	—	—	—	1.000

Note 2. Approximate solution for multi-conductor cable.

If a charge of Q units per cm. is considered concentrated along a line having the cylindrical coördinates (d_0, π), the origin being the centre of a sheath of radius R which is at zero potential, the potential function within the sheath is, by the method of images

$$V = -Q \ln \frac{\rho^2 + 2\, d_0\, \rho \cos\theta + d_0^2}{\frac{d_0^2}{R^2}\, \rho^2 + 2\, d_0\, \rho \cos\theta + R^2} \tag{13}$$

The equipotential surfaces of equation (**13**) are circular cylinders whose axes have the coördinates

$$\rho = d_0 \frac{R^2\,(1-c^2)}{R^2 - c^2\, d^2}, \qquad \theta = \pi$$

and whose radii are equal to

$$r = R\, c\, \frac{R^2 - d_0^2}{R^2 - c^2\, d_0^2}$$

where c equals the base of natural logarithms raised to the $-\frac{V}{2\,Q}$ power, V being the potential of the cylinder in question.

When more conductors than one are placed symmetrically in the same sheath, the potential function may be found approximately by adding terms of the form (**13**), the angle θ being changed to correspond to the position of the new conductors.

Note 3. Bibliography.

Below are given some references in addition to those given in the foot-notes of the paper.

(*a*) High Voltage Insulation

1. Factor of Safety for High Tension Electrical Apparatus. *Electro. Zeitschr.* Aug. 26, 1909.
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DISCUSSION ON "POTENTIAL STRESSES IN DIELECTRICS". NEW YORK, OCTOBER 14, 1910.

J. B. Whitehead: The language of the ionization theory is conspicuously lacking in this interesting paper. Since this theory is now widely accepted, and since practically all of the phenomena of the conductivity of gases and many of those of liquids and metals may be explained in terms of this theory, it is worth while to consider in the same light some of the questions raised in the authors' valuable summary and discussion of the nature of the processes involved in the break-down of cable insulation. First as to the possibility of corona in solid dielectrics it must be remembered that the term " corona " has arisen in connection with the phenomenon in gases and that the structure of the solid is radically different as viewed by the firmly established kinetic theory of matter and its offspring the ionization theory. The important differences in the present instance are the greater number of free ions in a gas, the greater length of their free paths, and above all the possibility of an ion attaching itself to one or more molecules and dragging them through the gas under the influence of an electric field. Thus in the corona in gases it is certain that disruption or ionization occurs only within the bounds of the corona itself, yet beyond the corona there is motion of charged molecules the charges originating as free ions in the corona. Moreover it is highly probable that the gas even in the corona is not disrupted at all in the sense that the term means the separation under the electric field of the two component charges of an atom of molecule, but that these latter are split apart by the impact of a free ion of which there are always a certain average number present.

In the case of the solid dielectric on the other hand there is little, if any, evidence of the existence of free ions. The mean free path of the molecules is much shorter than that of the gas and it is certain that agglomerations of molecules attached to a free ion cannot move freely through the body of the substance. Further, it seems highly probable that the break-down of a dielectric is an actual disruption or tearing apart of the opposite charges of a molecule under the stress of the electric field. The long accepted view that the dielectric properties are due to an elastic structure of a molecule in which the two component charges are held together up to the point of disruption, is not in conflict with the ionization theory which simply states that there is no extended motion of free ions with consequent possibility of ionization by collision, and resulting conductivity.

What then does the theory offer in explanation of the facts observed in the behavior of cable insulation? These facts are: (*a*) The insulating material may be overstressed without break-down. (*b*) There is no evidence of corona or charring of insulation. (*c*) There is no evidence of conductivity after overstress or consequent increase of capacity due to such conductivity. (*d*) The material after overstress is, however, weaker.

There is no difficulty in the idea of a strain of dielectric material beyond the electrical elastic limit with no resulting structural break-down and resulting conductivity. In a single conductor cable, we may think of a string of molecules stretched radially along a line of electric force. When the interior portion of the insulation is overstressed, but the insulation as a whole unbroken we may think of the component charges of a molecule in the stressed region as drawn apart, and a tendency on the part of opposite charges of two adjacent molecules to combine. If this tendency could take place along the whole line of force there would be combination throughout and resulting discharge. The phenomenon would then be similar to conduction in a metal. In the case as supposed, however, the outer portions of the insulation are not overstressed, consequently proceeding outward from the conductor along the line of force there comes a region where there is a molecule which is not overstressed, which therefore successfully resists the tendency of one of its charges to pass to the adjacent overstressed molecule. This restraining influence is therefore propagated backward toward the center and serves to keep the overstressed portion from breaking down entirely. In this way the region of safe stress may be said to aid that in which this stress is exceeded. Referring to fact (*b*) it should be noted that the corona as it is known in gases with its evolution of heat is probably due to the rapid motion of charged particles or ions through the body of the gas. There is not the possibility of such motion in dielectrics and it is not therefore a necessity of overstress that there should be the carbonization usually resulting, in dielectrics from the passage of current. As to fact (*c*) it is evident that if there is no break-down and resulting conductivity there is no reason why increase of capacity should be looked for. There remains the fact (*d*) that the material is weakened electrically after being overstressed. In explanation of this it may be pointed out that slight impurities of material, particularly if such impurities have large conductivity, would serve to enable the opposite charges of adjacent overstrained molecules of the dielectric to be neutralized thus leaving an unbalanced molecule and a consequent region of weakness. This action would naturally take place in the method ingeneously described by the author with the term " needle point ".

With regards the question of the constancy of the electric strength of dielectrics it may be pointed out that there is plentiful evidence that in gases the electric stress may be carried far beyond the value which is taken as constant for the material for the great majority of circumstances. In those instances in which the gas seems to present abnormal strength it may be shown that the conductor applying the electric strain has dimensions so small as to be comparable with the mean free paths of the ions which are involved in the break-down of the gas itself. Extending this idea to the case of dielectrics we are faced with the fact that the distances between the ions which enter into the phenomenon of disruption are very much smaller than those involved in the phenomena occurring in gases. It would therefore seem probable that by steadily decreasing the size of wire any tendency of the electric strength to present an apparent increase must occur at very much smaller diameters than those obtaining in the case of a gas. It is worth mentioning also that for the same reasons one might expect an alteration in the value of the specific capacity of the material for very small wires.

The paper has presented in valuable fashion the problems connected with the strains in the insulation of cables. It leaves the field in excellent shape as a point of departure for promising experimental work. It is to be regretted that the author could not supplement his own deductions with more experimental evidence. The field, however, is notoriously a difficult one.

Milton Franklin: The subject of this evening's paper is of great interest to me inasmuch as I have done some work along these lines myself. I have prepared a paper on the analytical discussion of the physical dimensions of cylindrical dielectrics. My paper is mathematical rather than practical, though only the simplest mathematics are involved. The author has applied these principles to commercial design, which is, after all, the ultimate aim of all such investigations.

My analyses, however, are fairly exhaustive and will enable any one to comprehend the principles involved and to extend their application to many cases other than the insulation of cables, and to cases of this, other than to those here treated, for example: the determination of the minimum mass of material that may be used in any case, etc.

The paper this evening is a very practical one, and in my opinion admits of very little criticism. The attempt to explain the cause of dielectric failure seems to me to be a description of observed cases rather than an explanation.

I have shown in the paper referred to, and in some subsequent experiments, that the dielectric stress corresponds to a mechanical stress similar to a hydrostatic pressure and accompanied by a proportionate strain, and have given an equation expressing the values of this stress, for various conditions in pounds per square inch. I am led to the conclusion that the failure is due to the periodic application of this stress, and the ultimate fatigue of the material. It is true that the stress and the consequent strain are small, but the number of blows is enormous, *e.g.*, at 60 cycles per second there are one hundred and twenty blows per second, 7200 blows per minute, 432,000 blows per hour, 10,368,000 blows per day, etc. This I think explains the cause of failure, the needle point result being due to lack of homogeneity and constituting the prodromata of an unstable equilibrium. The delay, or time lag, observed is not incompatible with this hypothesis.

With respect to the cases given for multi-conductor cables, I cannot agree with the assumption of the author with regard to the distribution of charge. He seems to ignore the influence of electrical images and the oscillating character of the alternating current, for which, in the main, these cables are designed. With respect to images it should be noted that in cables the conductors are very near the ground, *i.e.*, the images, and the skin effect tends to a peripheral distribution of the charge. The moments of these quantities are not amenable to mathematical analysis and evaluation, but I am satisfied from observation of practical cases that the assumption of uniform peripheral distribution, while probably not exact, will lead to minimum errors. This applies also to practical cases of transmission.

A. E. Kennelly: The subject of this paper is of great practical importance owing to the rapidity with which voltages have been rising recently in electrical engineering.

The facts are very clearly presented in the paper. The paper has, moreover, the special merit of presenting curves, by means of which the advantages, theoretically obtainable from the grading of cable insulation can be read off on inspection. We should however, carefully distinguish between the advantages that may be theoretically obtainable, and those that may be practically obtainable, through grading. Many considerations, such as mechanical strength, elasticity, permanence, cost, etc., must be taken into account, besides the dielectric strength, in selecting gradings.

We all know that a joint in the magnetic circuit gives rise to a certain extra magnetic reluctance and c.m.m.f. But the paper shows that a joint in the electrostatic circuit may not merely be the seat of additional electrostatic reluctance, but also of a dangerous local electric gradient. Such electrostatic joints may be inimical, by introducing equivalent point conductors, where the dielectric may break down, as little spherical particles into conducting material, whence electric flux and electric equipotential surfaces may diverge anew with powerful local intensities into the adjoining layers of dielectric. For this reason also the paper indicates that a grading of insulation may be detrimental instead of helpful.

It must be admitted, however, that the particular kind of grading experimented with—the grading of rubber and glass—is more than usually dangerous in regard to weak electrostatic jointing. When a rubber-covered wire is pulled into a glass tube, there is sure to be a layer of air included between the two. This air has not only a relatively high electrostatic reluctivity, thereby establishing a relatively large drop of potential across the layer, but it has also a relatively low breaking stress. Once it breaks electrically, it is able to precipitate high local stresses near the broken down spots, as is described very clearly in the paper.

In making computations of graded electrostatic reluctances, "semi-log" paper has special advantages, that is, paper ruled to logarithmic coördinates along the axis of abscissas, but to ordinary uniform spacing along the axis of ordinates. "Semi-log" paper can be constructed by taking ordinary cross-section paper, and laying off the spacings, from the face of a slide rule, along the horizontal axis. The long denominator in formula (3), which is virtually a summation of electrostatic reluctances in series, is then presented on "semi-log" paper in the form of a simple series of juxtaposed rectangles. The total area of all the rectangles is thus easily determined, and defines the total electrostatic reluctance of the graded insulation. The potential in the layers insulation also reveals itself on the "semi-log" diagram, as a series of connected straight lines.

In regard to the effect upon the electrostatic capacity of dielectrically stressing cable insulation layers, I may mention a case that came to my notice a few years ago. A stranded copper conductor 2.3 mm. in diameter, was covered with a layer of Para rubber to a wall thickness of about 1 mm. and then covered with vulcanized rubber, containing over 40 per cent of rubber, to a total diameter of 7.15 mm. About one hundred 5-mile lengths of this core were tested. The tests included electrostatic capacity, and dielectric stress at 5 kilovolts r.m.s. pressure between conductor and outside salt water, for 5 minutes, at 60 ~. It was found that the core easily withstood this pressure, and no injury could be detected in the insulation after this application. The linear electrostatic capacity, however, which, before applying the dielectric test, averaged approximately 0.4 microfarad per nautical mile, was distinctly increased after applying the test. The increase was most noticeable immediately after the test, and partly disappeared with time; but an increase of about 5 per cent was found to persist, at least for months. In some cases the increase in linear capacity immediately after the test was 15 per cent. The capacity was measured by direct current methods, using (1) galvanometer deflections on charge; (2) galvanometer deflections on discharge; (3) the method of zero resulting charge by mixture.

W. S. Franklin: In discussing a theoretical paper on engineering one should attempt first of all to estimate the significance and value of the paper. In the present instance this duty is a pleasing one because in my opinion the paper constitutes an unusually important and really practicable application of theory to electrical engineering.

I have always looked upon the grading of cable insulation as an extremely simple matter, which indeed it is from the theoretical point of view. But the grading of cable insulation is not wholly a theoretical matter; the facts as to the electric strengths and inductivities of available materials are of some importance, to say the least, and Mr. Osborne is the first, as far as I know, adequately to consider the question of grading on the basis of these facts.

The case mentioned by the author of a cable which contained four times the necessary volume of insulating material shows indeed the importance of the paper, and the fact that a person perfectly familiar with Maxwell's theory would be unable to point out this glaring case of bad design shows that something besides Maxwell's theory is necessary.

There is a close analogy between the mechanical cracking of strained glass and the electric rupture of a dielectric. The author seems to have this analogy in mind when he speaks of the "needle-point" theory. This analogy is developed in Nichols & Franklin's *Elements of Physics*, Vol. II, pages 154-157. The analogy holds for the ordinary spark discharge and also for the brush discharge or "corona," and it is not inconsistent with the electron theory provided one does not look upon the "needle-point" fracture as a mathematical line.

A difficulty in forming a mechanical conception of the influence of inductivity on the distribution of electric stress is that a mechanical arrangement *in parallel* must be compared with an electrical arrangement of dielectrics *in series*. Thus a number of helical springs of different degrees of stiffness are placed in parallel between two parallel metal bars. When these bars are moved towards each other every spring is subjected to the same strain or yield and the stress or compressing force is great in the stiff springs and small in the springs which yield easily. When a number of layers of dielectric are placed between two charged flat metal plates, they are all subjected to the same electrical yield (electrical flux density or displacement), the dielectrics which have great electrical stiffness (small inductivity) are subjected to great stress in volts per centimeter and those which have small electrical stiffness (large inductivity) are subjected to small stress in volts per centimeter.

The modern built-up cannon furnishes a close analogue to the graded cable. Indeed, if one could use highly elastic or easily yielding steel for the inner portions of the gun tube and less elastic or stiffer steel for the outer portions (ultimate strength of steel being the same in both cases) then the analogue would be complete. The interior portions of such a graded steel tube would yield greatly in being brought to their maximum permissible tension and this great yield would stretch the outer and less yielding portions of the steel tube sufficiently to bring the tension in these portions to the permissible limit. So it is in the graded cable; the inner portions of the insulation have high inductivity, that is to say, the inner portions are made of material which is electrically yielding, as it were, and the great yield (electrical flux density or electrical displacement) which is produced in the inner layers as compared with the outer layers of insulation causes inner and outer layers to be stressed simultaneously to their maximum strength in volts per centimeter.

W. I. Middleton: Considerable is to be gained by the grading of insulation of cables for very high voltages, say above

15 kilovolts, as it tends to decrease the wall of insulation and so reduce the cost of outside covering; but on lower voltages its advantage is doubtful, where grading might reduce the insulating wall to such an extent that for mechanical reasons it would be dangerous. Cables carrying from 10 to 15 kilovolts, where the copper runs from No. 1 to No. 4/0 B. & S., can easily be made with a good grade of rubber without putting too great a strain on the dielectric. Owing to the difficulty of making insulations of different specific inductive capacities when only one kind of dielectric is used, it would seem best in making graded cables to use a combination of two or more materials, such as rubber, cambric, and paper.

I am most interested in what the speaker terms "Corona in Solid Dielectrics.". I do not believe any of us knows what actually takes place in the dielectric, but as far as Professor Russell's hypothesis, that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excessive voltage in either rubber or cambric insulation. I do not say that some cables may not be injured electrically by overstraining, but cables that are easily injured by voltage stress are to be avoided, as this injury shows that they have not been as well made as is possible. There is a vast difference in the characteristics of rubber compounds, which is not important for low-voltage cables, but is very important for high-voltage cables.

Now to come directly to the corona law and its application to cables, I agree to the commonly accepted formula

$$V = K\, d \log \frac{D}{d}$$

where V = test pressure.
K = voltage constant of the dielectric.
d = copper diameter.
D = diameter over insulation.

so long as the copper diameter is greater than 10/27 of the diameter over the insulation, that is, to the point where d equals $\frac{D}{2.72}$. Taking D and d in mils, we have tables showing the values of $d \log \frac{D}{d}$ for all sizes from No. 18 B. & S. to 1,000,000 cm., with walls from 1/32 to 20/32 in. on each size. We have used these tables to the critical point where d equals $\frac{D}{2.72}$, or approximately where the copper diameter and insulating wall are equal, but beyond this point the formula does not apply.

For example, when the formula demands 45/32-in. wall on a No. 14 B. & S. wire for a voltage, on which 5/32-in. wall is adequate on a No. 4/0, we know this wall is not necessary. If the formula beyond this point does not apply, what formula does apply?

Having in mind the law for corona in air and the possibility of its application to solid dielectrics, I suggested that results be worked out with a modified formula, where d is changed to d_c and $d_c = \frac{D}{2.72}$

$$\text{so that } V = K\, d_c \log \frac{D}{d_c}$$

This necessitated working out new values for our tables, and we began on No. 6 B. & S. for walls from 5/32 to 20/32 in., 5/32 in. being the point at which the wall of insulation is equal to the copper diameter. Inspection of the new tables shows a surprising feature, namely that the new values for $d_c \log \frac{D}{d_c}$ increased about 10 for each thirty-second added to the wall, while in the old table these values showed a gradual decreasing increment. As soon as we noted this feature, we made a further study of our formula, and saw immediately that the increase in value for 1/32-in. increased wall was a constant, regardless of the size of the cable, and calculation showed this constant to be 9.9855.

The two formulas agree that there is a minimum outside diameter for a given voltage, but they do not agree in the fact that while the old formula calls for an increase in the outside diameter with a reduction of copper, the modified formula allows for a reduction of the copper with the same outside diameter.

In a previous attempt to check up the old formula, we had made tests on a series of small conductors insulated with relatively thick walls of rubber, but the results did not agree at all with our calculations. On making a comparison of figures obtained by the modified formula with the old tests, we found that they checked up in a most satisfactory manner, and the modified formula has agreed with the results of subsequent tests.

It may be interesting to mention that instead of the 45/32-in. wall required on the No. 14 wire in the example given above, we now figure that only 9/32 in. wall is necessary.

Henry A. Morss: I would like to explain in a little more general way than Mr. Middleton has done, why he has developed his formula. When we first made cables, we had no means of knowing the necessary thicknesses of insulation except by experience, and if we wanted to determine the thickness for a cable on which we had no experience, we could only guess. Then we began to learn about this formula $d \log D/d$, and found that by taking its values and multiplying by a constant, which we could determine by experiment, we could arrive at a suitable thickness of insulation for any voltage. This worked very well, and we were much pleased with it until we began to figure small wires for high voltages. Then, as Mr. Middleton said, we came to absurdities; that is, they were absurdities to the extent that we knew we needed no such thicknesses. What we have been working toward, and have been trying to get, is some rule by which our calculated thicknesses will compare properly with the thicknesses obtained by experience, and this modified formula which Mr. Middleton has developed, seems according to our experience to date to enable us to figure these thicknesses which we could not figure before.

R. W. Atkinson: Assume as true (as seems probable) the author's theory that the overstressed portion of the dielectric is punctured in "needle points" and that the potential across this portion remains equal to that required to cause breakdown. Now the current across this portion is greater than the charging current at this voltage. The extra current is conduction current and is at right angles with the charging current and in phase with the voltage across this portion. The resultant current is then less than 90 degrees ahead of the voltage. Hence when this voltage combines with the voltage across the remainder of the insulation, the resultant is less than the numerical sum. The net result is that the capacity is greater than would be calculated by the method suggested by the author and used as a basis for curve *c* in Figs. 10 and 12. This difference would not however be marked until the voltage is considerably higher than that which causes partial breakdown and would not be observable at all on ordinary cables with the usual insulation thicknesses, since there is not so marked a difference in the maximum and minimum stress as to make it possible to raise the voltage greatly above that causing partial breakdown.

Another thing which might be expected in the test is an increased dielectric loss when the conduction begins. It would be impossible to predict the amount of this since it is quite possible that the voltage across the needlepoint punctures is reduced considerably below that originally causing them. The destruction or carbonizing of the insulation by corona cannot be due to heat when the dielectric is uniform. Were it sufficient for this, the whole cable would heat extremely rapidly and the loss would have readily been observed in the wattmeter measurements both by the author and by Höchstädter. (In *Elec. Zeit.*) The charring of insulation by discharges where there are air spaces is of a different nature.

H. W. Fisher: I will not attempt at this time to discuss the mathematics of the paper, but rather the experimental part in the light of recent investigations and reason.

During considerable experimental research work, I have never had any evidence which would lead me to the belief that the insulation next to the conductor in an overstressed cable becomes charred. It has been impossible to manufacture a cable whose insulation at all points will have an equal resistance to disruptive voltages. Hence, for sometime, I have believed that breakdowns of over-stressed cables must be caused, in the first place, by a gradual puncturing of the insulation around the conductor at the weakest point.

A knowledge of the characteristics of manufactured insulations leads one to the belief that an absolutely continuous disintegration of overstressed portions is impossible, and therefore, until an actual breakdown between conductor and sheath occurs, this action of isolated discharges must take place more or less all along the conductor.

I have noticed for many years that glass, overstressed at points by local discharges, breaks down under voltages much below what would ordinarily be considered safe. Generally, but not necessarily so, the glass is found to be cracked and I have been inclined to believe that the localized stress started a small crack through which a puncture immediately followed. The behavior of glass under localized electric stress very strongly accentuates my belief in the correctness of the author's conclusions as to isolated discharges along the conductor.

Had other materials, such as a paper insulated conductor inside of a hard rubber tube, been used, I doubt very much if the difference between the normal puncture voltage of the hard rubber tube and that of the improvised cable would have shown anything like the difference found in the case of the glass tube specimen.

It must be remembered that in the tests under consideration, the materials used were chosen so as to accentuate the stress on the insulation next to the conductor. Therefore, in the case of a regular high-voltage cable, it is more difficult to determine what actually happens to the insulation if overstressed.

In a series of papers recently published in the *Elektrotechnische Zeitschrift*, Mr. M. Höchstädter gives the results of tests which show that the power factor increased very slightly with increase in the applied voltage, and that even at the puncturing voltage, there was no sudden increase of dielectric loss, which we would expect if there were a large number of discharges through the insulation near the conductor. Moreover, the general properties of the cable did not seem to be changed up to the instant when a puncture occurred. In the cable under consideration, the size of the conductor and thickness of insulation were such that the stresses on the insulation at the conductor would not be abnormally high compared with those on the insulation near the lead, and this may be the cause of the results obtained.

It would be interesting to make tests on an ungraded cable having a small conductor and considerable thickness of insulation and note if the dielectric loss increased rapidly when the insulation near the conductor began to be overstressed. Such a test I have had under consideration for some time.

One important fact must not be lost sight of, namely, that for mechanical reasons cables often have a thicker insulation than might seem necessary for the voltages under consideration.

The proper grading of the insulation of high-voltage cables is certainly of the highest importance and every up-to-date manufacturer will have his own way of doing this.

Percy Thomas: I will only add one suggestion. So far in the present discussion one of the very important elements governing the actual breakdown of insulating material has been practically omitted, that is the effect of temperature. Broadly speaking, in insulating materials, especially in some sorts of insulating material, an increase in temperature beyond a certain point, not far above ordinary atmospheric temperature, means a very great decrease in insulation resistance and more troublesome still a very considerable increase in the energy loss within the insulating material itself. The results of this fact may or may not actually be a serious matter, depending upon conditions.

Take for instance a comparison between the breaking down strength of a sheet of varnish covered paper one one-hundredth of an inch thick and the breaking down strength of fifty of those sheets piled together. The single sheet will stand perhaps 10,000 volts without trouble if the electrodes have not too sharp edges. Fifty of these sheets may very likely stand continuously not over 50,000 volts. This value might be a little higher if the material were well dried. Now as the number of sheets is multiplied by fifty and the breaking down voltage only by five there is a loss of possibly ten to one in the capacity of each sheet to withstand voltage. This effect is largely a result of the increase in temperature within the body of the material, not necessarily throughout the material, but at some particular spot or spots or layer. The higher temperature means that the energy loss will be larger which larger loss will cause the temperature to rise and this rise in temperature again increases the local loss of energy at that particular location and so on up and up. The heat resisting character of the material prevents the dissipation of heat fast enough to keep the temperature down. The result may be the entirely confined to one portion of the insulating material near the center, while the rest may be entirely uninjured. I have often observed such effects. Of course, extreme results are to be expected only under favorable conditions as where the insulation is very thick and has naturally a high energy loss under voltage stress.

This trouble is not met with in cables with the usual thicknesses of insulation under ordinary conditions, because they are used so far below the breaking down point of the insulation that the energy losses are not sufficient to produce a material rise in temperature. It is only as we approach very close to the puncture point that the critical rise in temperature is found.

I think that it may be very likely that in the experiments described in this paper this local heating had a very important part in the final result, but it would be practically impossible to trace out this fact afterwards. I am not familiar with the thicknesses of material used, nor with other conditions of the test.

In tests of this sort, the time of application is of course extremely important as a certain elapse of time is necessary to cause a rise of temperature. The difference between the application of a static stress lasting but momentarily and a continuous application of alternating voltage is of course extreme.

The phenomena accompanying the case of two or more layers of insulation with a slight enclosed amount of air between, is a difficult one; but doesn't it seem probable that the heat generated in the thin layer of air by the fact that its insulation strength is overcome and the ions and corpuscles are freely moving therein and therefore generating heat, has much to do with the very serious weakening the total insulating strength of the combination found to accompany the presence of air layers?

If we were nearer the breaking down strain in cables, the effect of I^2R in the cable itself, due to the useful current flowing through the copper might be important. Fortunately, however, the cable has too good a radiating power for this loss to be critical, except possibly in the case where the grounding of one leg of the circuit occurs or excess voltage from some other cause subjects the cable to almost the puncture stress.

Possibly the effectiveness of the needle points in puncturing glass is very much emphasized by the point Professor Franklin has brought out, namely that we may easily have a minute crack started in this material. Now this crack is very likely due to the concentrated generation of heat, due to the extremely local application of potential by the needlepoint. Rapid heating of the glass at one spot would be almost sure to crack the glass at this point, the physical weakness of glass in that respect making it particularly vulnerable. This difficulty would not be found to the same extent in rubber or paper or cambric.

C. J. Fechheimer: The conditions which obtain in alternators are somewhat different from those which apply to cables, bushings and transformers, inasmuch as, due to mechanical considerations, we are practically compelled to place the conductor in a slot which is usually rectangular in section. The ideal condition, from the standpoint of insulation only, would be that of a round slot by means of which we would eliminate sharp corners on the coils. This, however, is impracticable.

In order that we may use as economically as possible the most valuable space in high voltage generators—that is, the stator slots—we often use conductors which are square or rectangular in section and to avoid the stress in the dielectric at the corners of the coil reaching too great a value, the corners of the conductor are usually rounded.

It has often been contended that it is inadvisable to use mica for slot insulation and many engineers prefer only the use of cloth treated with some form of insulating varnish, but, as has been shown so well in this paper, it is extremely advisable to grade the insulation; that is, place mica or some other dielectric having a high specific inductive capacity near to the conductor and some other dielectric, such as varnished cloth, having a specific inductive capacity of about half that of mica, on the outside of the coil.

This grading of insulation enables us to use a smaller quantity and we thus can place more copper in the same size slot than we could if we used only varnished cloth for insulation. This also has the additional advantage that with a thinner insulation the heat can flow more rapidly from the conductor to the outside of the coil; and furthermore the mica, being near to the copper, is subjected to the highest temperature, and this material has the inherent property of being able to withstand high temperature far better than any kind of cloth.

The great advantage to be gained by placing the material having high dielectric strength, as well as high specific inductive capacity, next to the copper was brought out by Professor H. J. Ryan in his paper on "High Pressure Insulation" at the Electrical Congress in 1904, although he is inclined to believe that "structural requirements make impracticable . . . . . the placing of the most powerful dielectric next to the conductor".

We have since found, however, that we can without great difficulty surround the conductors with flexible mica and then use as a binder the varnished cloth or linen tape. A coil which was recently made on this principle in accordance with Mr. H. Pikler's advice, was wound with No. 8 B. & S. square wire having a radius on the corners of 0.026 in. The coil, after winding, was vacuum treated and was then wrapped with two layers of 0.012 in. flexible mica and then with two layers of 0.009-in. varnished cloth and one layer of linen tape. The coil was dipped in insulating varnish a number of times between wrappings. When subjected to a high-voltage test, this coil withstood a puncture test on one side of 29,000 volts and on the other side of 30,000 volts, these being effective values of voltage with a sine wave.

I was in hopes that I might reduce the density of dielectric flux at the corners, and thus increase the break-down voltage by placing tinfoil around the conductor, and also between the mica and varnished cloth and therefore had a coil wound similar to the one described above with the exception of placing tinfoil as stated, but found that this coil broke down at 16,000 volts; and another coil, which had tinfoil between the conductor and mica only, broke down at 20,000 volts. Violent brush discharge indicated that the insulation was highly stressed before breakdown.

It would appear to me that the tinfoil has the effect of increasing the electrostatic capacity of the layer of mica and decreases that of the varnished cloth as implied in this paper, thus raising the potential gradient in the varnished cloth and decreasing it in the mica, causing the varnished cloth to break down, which resulted in the mica taking all the stress, and this broke down soon afterward. Had the tinfoil between layers of insulation proven a success as far as increasing the breakdown voltage was concerned, I would have expected trouble from eddy currents in the tinfoil due to changing in interlinkages with magnetic flux. This I thought I might be able to overcome.

In this connection I would call attention to the following statement in the paper: " Since these electric strengths are limited at present, in the manufacture of cables to very few values, they are not properly considered variable ". From the data which I have available, it is my impression that the dielectric strength of mica in volts per millimeter is nearly twice that of varnished cloth; so that for the ideal grading of potential we should be able to have the stress in the mica, in volts per millimeter, practically twice as great as in the varnished cloth. In fact, it appears to me that for ideal grading of insulation we should have the ***maximum potential stress in each dielectric proportional to its breakdown voltage.***

I would call attention at this time to a slightly different conception of the problem than that given by the author in his paper. As stated by Professor Ryan and others, the breakdown of insulation results from the density of dielectric flux reaching a certain critical value just as in the case of material in tension or compression, a rupture occurs when the stress expressed in pounds per square inch, or similar units, reaches a certain critical value. It would seem that this view would give a clearer physical conception of the phenomenon than that of considering the breakdown to be due to the potential per unit thickness reaching a critical value. After all, as Dr. Steinmetz states in his book on " Transient Phenomena ", the potential is merely a mathematical fiction which is taken to be a measure of the electrostatic field, and we should therefore consider the stress in insulation to be due to the dielectric field rather than to the potential. Of course, for mathematical analysis it is far easier at present to treat the subject from the standpoint of potential rather than from that of dielectric flux.

From my point of view it appears that two dielectrics having equal strength expressed in volts per millimeter, but having different specific inductive capacities, the dielectric having the higher specific inductive capacity transmits more dielectric flux for the same difference of potential per millimeter and therefore its stress expressed in lines of dielectric flux per square centimeter is the greater.

If, as in the case of cables, we place a dielectric having a high specific inductive capacity next to the conductor and a somewhat lower specific inductive capacity dielectric outside of this first dielectric, then the first dielectric has the greater stress expressed in lines per square centimeter, although the volts per millimeter may be the same as in the outer layer of insulation. The effect of the outer layer in addition to taking part of the stress, is (due to its lower specific inductive capacity) to prevent as great a flow of dielectric flux as would be the case if all of the insulation were made up of the insulation having the higher specific inductive capacity.

G. I. Rhodes: This paper on potential stresses brings out three points to which I wish to call attention: the so-called corona effect, the value of graded insulation and the effect of heating by the load.

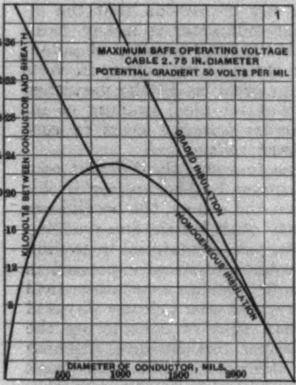

FIG. 1

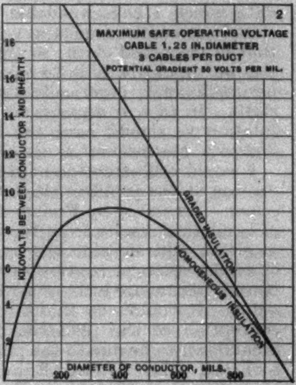

FIG. 2

The theory offered in the paper for the deterioration of insulation under excessive voltages, has an interesting bearing on the test voltages which should be applied to cables. These over-voltage tests are now applied on high tension cables at twice the working voltage for a period of 60 seconds.

When underground cables were first used, dielectric tests were frequently applied at voltages as high as three times normal for periods as long as half an hour. Breakdowns occurring during these tests usually happened within the first minute, but at times the cable held up for almost the entire test period. These breakdowns occurred with no apparent weakening of the rest of the cable.

The needle point deterioration, as explained in the paper, accounts for this phenomenon. If the deterioration was general these high voltage tests would have weakened the entire cable. The theory of failure in a gradually extending needle point explains both the time element and the apparent absence of damage to the rest of the cable.

In Table I the author gives an idea of the maximum voltages for which cables can be built. The limit of size is the maximum that can be drawn into a three-inch duct. I wish to call attention to the fact that high voltage is not necessarily the criterion by which to judge the value of a cable. In the future development of high tension underground transmission, it is probable that in addition to high voltage, a large safe load per duct will be called for. A small percentage loss will also be a factor. The cable will then be valued in proportion to its ability to carry load and inversely as the percentage loss at the maximum safe load.

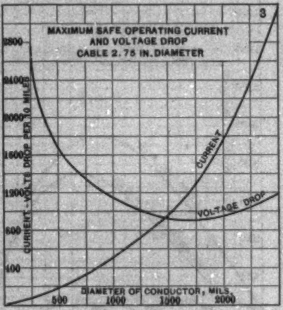

FIG. 3

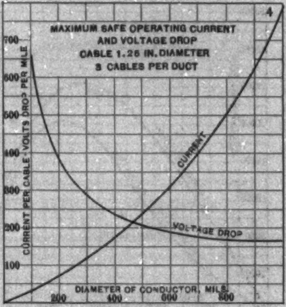

FIG. 4

I have prepared some curves, showing roughly the voltages, loads, losses, etc., in cables. The first type of cable considered is as large a single conductor as can be drawn into a standard duct. The second type is a single conductor, so large that three can just be pulled into a standard duct.

Fig. I shows the relation between permissible operating voltage and diameter of conductor in a cable of the first type. The figures are based on equation (2) of the paper. The voltage gradient of 50 volts per mil is safe for paper insulation. Curves are shown both for homogeneous insulation and for the ideal grading. It will be observed that there is a definite maximum voltage for homogeneous insulation, which obtains with a conductor diameter about 40 per cent of the total outside diameter of insulation.

Fig. 2 shows the same curve for the second type of cable, three to a duct. This type of cable was taken rather than the usual three-conductor cable, to simplify calculations. The results should not be very far different. It will be observed that the maximum voltage for homogeneous insulation again occurs at a conductor diameter of 40 per cent. The total actual value of the maximum is reduced by the small diameter of the cable.

Fig. 3 shows the maximum safe current in the 2.75-in. cable and the voltage drop due to this current. The effect of the relatively low heat conductivity of the insulation is taken into account. These curves are only roughly approximate.

Fig. 4 shows similar curves for the 1.25-in. cable. Here the currents are smaller, but current densities larger than in the previous case, principally on account of the thinner insulation.

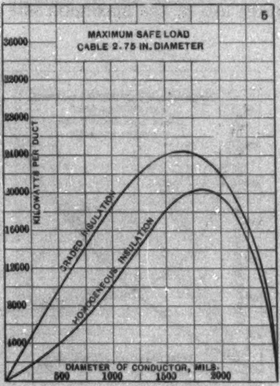

FIG. 5

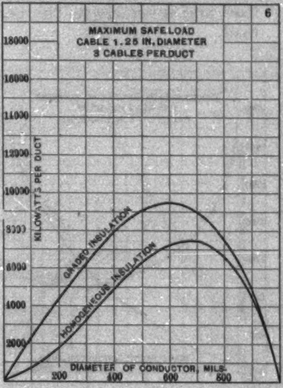

FIG. 6

Fig. 5 shows the relation between conductor diameter and maximum safe load on a 2.75-in. cable for the two kinds of insulation. It will be observed that the improvement due to grading the insulation is less here than on the voltage curves. The maximum loads require larger conductor diameters than the maximum voltage. This best diameter is approximately 70 per cent, instead of 40 per cent.

Fig. 6 shows similar curves for the smaller cables, three in a duct. Here the same general characteristics are seen as for the larger cable, except that the best conductor diameters are slightly lower.

Fig. 7 shows the percentage heating losses per mile in the large cable for the two types of insulation. Here the best conductor diameters are lower than for maximum load.

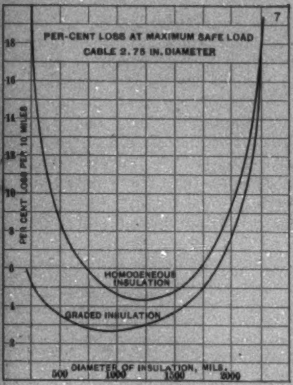

FIG. 7

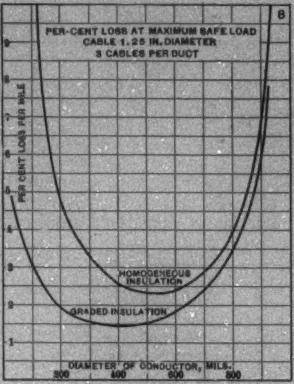

FIG. 8

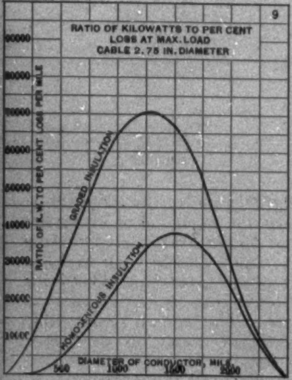

FIG. 9

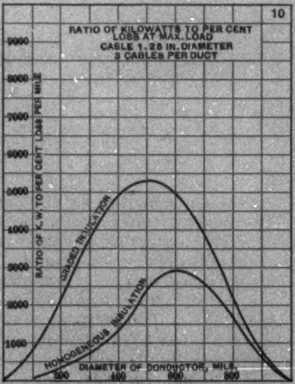

FIG. 10

Fig. 8 shows these same curves for the smaller cables. The effect of the high current density and the low voltage make the losses relatively high.

In Fig. 9 there are combined the loads and the losses, to get the measure of the value of the cable described at the beginning of this contribution. It is seen that the best diameter of conductor is from 50 per cent to 60 per cent of the total. Grading the insulation improves the cable about 80 per cent.

Fig. 10 gives similar curves for the smaller cables. It is seen that small cables are very much less desirable than the large. This is due to the lower maximum load and the larger losses.

To summarize the curves, it thus appears that the voltage to give the maximum capacity per duct is that corresponding to conductor diameter 70 per cent of the total, allowing 6,500 volts for the three cables per duct and 18,000 volts for the large cable. The benefit from grading the insulation is small. For minimum drop the conductor diameter is about 45 per cent, corresponding approximately to the highest voltage permissible with uniform insulation, 9,000 volts for the three phase cables and 23,000 for the large, single conductor cable; the improvement due to grading being 60 per cent in such case. The best all-round cable is assured with a conductor diameter of about 55 per cent, corresponding to voltages of 8,000 for the three small cables, and 20,000 for the large single cables. The gain, due to grading is about 80 per cent.

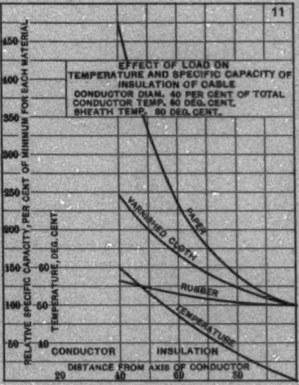

FIG. 11

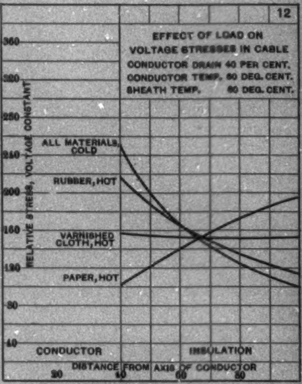

FIG. 12

If other than the maximum loads are to be considered, curves of somewhat different characteristics are obtained. These curves show only maximum conditions. They show the cable that will transmit the maximum amount of power per duct with the minimum loss. Other considerations are neglected.

In the paper the effect of the temperature gradient in the insulation is mentioned, but no figures are given. Figs. 11 and 12 show the magnitude of this effect. They are based on data published by one of the large manufacturers of cables. Fig. 11 shows the variation of temperature and specific capacity of the dielectric with distance from the sheath.

The material used has a very great effect on the capacity distribution. Fig. 12 shows corresponding voltage stresses with a constant potential difference between conductor and sheath. The three materials considered show very well the effect of the temperature on the distribution of the strains. Rubber, which has a very small capacity temperature coefficient, shows very little change. Varnished cloth, which has a considerably larger coefficient, has a potential distribution corresponding closely to that in a perfectly graded cable. Paper, which has a still larger coefficient, shows a reversal of stress, so that the greater potential gradients are near the exterior of the insulation. This effect represents overgrading. If the safe voltage with a cold cable is taken as 100 per cent the safe voltages, after heating due to load as shown in the curves, are 118 per cent for rubber, 160 per cent for cloth, and 128 per cent for paper. It is thus evident that the cable is safer when cold, the factor of safety being greatest where the thickness and the capacity temperature coefficient of the insulation combine to produce ideal grading. If the temperature coefficient is too great, the stresses are inverted and then there is less improvement due to load.

If the cables are to be graded at all, this grading should take into account the temperature distribution in the dielectric, so as to produce the safest cable under conditions of full load.

Armin Henry Pikler: The author in his very interesting paper properly started with quoting Maxwell. The fundamental phenomena in connection with dielectrics were observed by Faraday and the laws of distribution of the electrostatic flux in the dielectric of condensers of various configurations and finally the capacities of condensers of various configurations were given by Maxwell.

The results which Maxwell arrived at were not utilized for practical purposes until the necessity arose for them. It seems natural that the cable manufacturers, who were most pressed for room for insulation of cables, made first use of them. It was Professor Jona of Italy, who first made practical use of the idea of potential gradient and the grading of the insulation of cable.

From the analysis of two equations, the practical requirements for insulation between conductors arranged concentrically can be seen at once. From the equation: Potential difference equals charge divided by capacity, it will be seen that in condensers connected in series the one having the smallest capacity will have the greatest difference of potential between its conducting surfaces. From the equation giving the capacity of a cylindrical condenser $C = \dfrac{K\,l}{2 \log \frac{r_2}{r_1}}$ it will be seen that if the dielectric between the inner and outer conducting surfaces of the cylindrical condenser be divided into concentric layers of equal thickness, the inner layers—that is, the layers of the smaller radius—offer a smaller surface to the dielectric flux than the outer layers, when a charge passes from the inner to the outer wall of the cylindrical condenser. This results in a greater dielectric flux density per unit area on the inner layers. These layers will then have a greater difference of potential between the limiting walls and will be subjected to a greater stress. If the inner conductor is of very small radius, the stress in the layer of the dielectric close to this conductor will be enormous and there may be no insulating material sufficiently strong to withstand the stresses when this conductor carries a current of high voltage.

It is the above considerations which will lead to the design of the most efficient transformer insulation. I wish to discuss this subject more particularly from the point of view of the insulation and construction of high-voltage power transformers. The ability of transformers to transmit high voltages and to withstand very high voltage strains has developed practically during the last six or eight years and I dare say that this is due, not so much to a more thorough knowledge of insulating materials and the use of new materials, as to the recognition of the great dangers of moisture in the insulation, the capability of extracting this moisture and afterwards keeping it out of the insulation.

I wish to state that I do not consider it practical to use graded insulation in transformers between the high- and low-tension windings or between the windings and the core. The introduction of metallic layers between high- and low-tension windings would result in very great complications as regards manufacturing, and the connection of these metallic layers to taps of the high-voltage winding would add a number of high-tension leads, the placing of which would be cumbersome and the insulation of which would require a great deal of room and involve expense.

The grading of the insulation of a high-voltage cable is a matter of necessity because the unequal distribution of the dielectric flux and the great difference in density of the dielectric flux between points on the inner layers and the outer layers of the cable cannot be eliminated.

In high-voltage transformers, if properly designed, this unequal distribution of the dielectric flux density can be almost entirely eliminated and therefore the grading will become unnecessary.

Moreover, while in cable insulation economy of space is highly desirable, particularly from the point of view of cutting down the thickness and weight of the dielectric, the most expensive of the materials; in transformers a certain minimum space must be allowed between high- and low-tension windings and between windings and core to serve as ventilating ducts, admitting the circulation of oil between these parts. This results in low heating and consequently reduction in weight of copper, the most expensive of the materials used in transformers. This space, which is necessary for the purpose of cooling, is in most cases of ample size for the purpose of insulating the present commercial transformers of the very highest voltages, if properly designed and constructed.

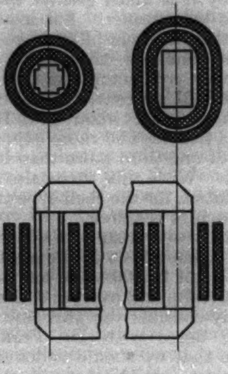

FIG. 1

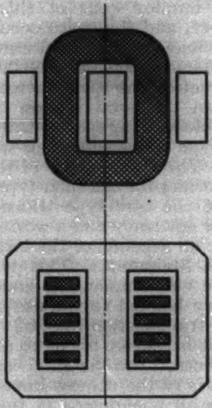

FIG. 2

The type of transformer where the distribution of the dielectric flux between high- and low-tension windings is most uniform is the one where the coils are arranged as concentric cylinders, either of circular or oval cross section. These two cylinders are placed over the sheet steel core in such a manner that the high-tension winding is outside of the low-tension winding. The opposing surfaces of these cylinders are either parallel walls or concentric circles of large radii. The percentage increase between the inner and outer radii being very small, the distribution of the dielectric flux between these surfaces will be fairly uniform and every cubic inch of dielectric will withstand the static strains in the same measure. The results will be a high factor of safety against breakdowns and economy in space and insulating material.

It will be only at the ends of these comparatively long cylinders that the density of the dielectric flux will be greater and its distribution irregular. These ends, however, being accessible, may be easily protected from breakdowns.

The type of transformer particularly adapted to employ coils and insulation as described above is the so-called core type transformer shown in Fig. 1. In contrast to this type, Fig. 2 shows another type of transformer winding, the so-called shell type. In this, the number of edges and sharp corners exposed between adjacent high- and low-tension windings and between windings and core are numerous. The dielectric flux density at these places is very great and it is difficult to insulate such windings. Nevertheless there is a great number of transformers, which employ coils of this type. The necessary insulation, however, and the space occupied by it is much greater than in the previously described core type transformer. For instance, in a 25-cycle, 2000-kw., 50,000-volt transformer of the core type construction the space factor of the windings—that is, the ratio between the total section of copper conductors to the total available winding space—will be about 27 per cent, whereas in the shell type transformer this space factor is only about 16 to 18 per cent. The consequence of this is a heavier and more expensive transformer for the shell type, about one-third more than in the case of the core type transformer. With this there also goes a lower efficiency and a worse regulation for the shell type transformer on account of the larger spacings required.

C. P. Steinmetz: This paper deals with a subject which has become very important, since the development of the electrical industry has led to the use of cables of 20,000 volts and more, and of transmission lines of 100,000 volts and over, and thereby made it necessary for us to seriously consider the phenomena of the electrostatic field. I entirely agree with Dr. Franklin, that it is of the utmost importance that we should endeavor to explain all phenomena in the simplest possible manner, and in such a manner as to get a clear physical conception of them, since only hereby it becomes possible intelligently and safely to use them. It is regretted therefore that the nomenclature and to the conceptions of the electrostatic field, electric intensity, electrostatic quantity, etc., are so cumbersome and so unamenable to giving a clear physical conception that we find it much more difficult to understand phenomena of electrostatic fields than for instance phenomena of the electromagnetic field. You can get a very simple and clear conception even of a very complicated magnetic field by Faraday's physical picture of the lines of magnetic force, and there is no reason why we should not get the same clear conception of the electrostatic field by a corresponding picture of the lines of dielectric force.

The first part of this paper deals with the question of grading in relation to cables, and the results and data given in the paper are very suggestive. But I believe we would make a mistake if we should use them as given, for the design of cables, for the reason that the conditions are much more complex than they appear from the discussion in the paper.

High-voltage cables probably never break down by their operating voltage, but they break down at a weak spot, an air bubble, a lack of homogeneity in the insulating material; or they break down by a transient over-voltage, an electric impulse of limited power but more or less unlimited voltage.

As regards the first, you see that fundamentally important in the design of cable insulation is the mechanical character of the insulating material, as thereon depends the probability of applying it without getting any weak spots or defects in it. An insulating material may have a very high specific capacity and high disruptive strength, and may therefore appear very suitable for the inner core of a cable, and still be entirely unsuitable, due to its mechanical characteristics which make it less safe to rely upon the absence of weak spots or defects in it. This very greatly limits the variety of materials which can be used.

As regards the second feature, when the breakdown is due to a transient voltage, it means that of equal importance with the two quantities considered in the paper—the specific capacity and the dielectric voltage—the *dielectric energy* of the insulating material enters into the design of a graded cable. It takes a finite amount of energy to break down a dielectric and the dielectric may be exposed to an electrostatic gradient far above the break-down gradient without breaking down or deteriorating, if the application of voltage is sufficiently short that the energy of the field is less than the break-down energy.

This makes the problem of grading very much more complex than it appears on the surface, when we consider that this latter quantity, the dielectric energy, is of equal importance to the two quantities considered, while quantitatively we know practically nothing about it.

The explanation of the deterioration of insulation when stressed beyond its dielectric strength, by the formation of pinholes, I do not consider as a hypothesis, but rather as a fact, fairly well known for some years. In the early days of the application of high-voltage cables it was suspected from the life history of these cables, that a deterioration of the insulation took place by the formation of pin holes, and evidence of this phenomenon was afforded by the investigation and study of the insulation in very high-voltage transmission systems. In those cases where the insulation had been locally strained beyond its dielectric strength under conditions where no secondary phenomena, as short circuiting arcs, had destroyed the evidence, it is common to find the surface perforated by innumerable pin holes which, in the case of a very high voltage transmission line, where the electrostatic energy is large, may reach visible size. If then the over strained insulation is perforated by pin holes, either microscopic or visible, the electrostatic field is brought to bear on the outer insulation in a concentrated form and the outer insulation is exposed to what we may call an electrostatic shearing strain. That explains the described break down of the glass tube at a voltage far below that which it would stand when exposed to a uniform static field.

This phenomenon has been described a number of times in recent years. It is shown best if you test a thin sheet of mica between a point and a plate. The mica sheet breaks down at a certain voltage. If now you put a drop of oil on the point, even a very small drop of oil, you find the mica sheet breaks down at a much lower voltage. In the first case, brush discharges spread from the point over the mica and give a gradual slope of the potential gradient. In the last case the drop of oil, by its much higher dielectric strength, cuts off the formation of the brush and brings the voltage localized to bear on the dielectric and the electrostatic shearing strain, if I may use that term, cuts through at a much lower voltage than a more uniform field would. You know that this phenomenon is guarded against in cable installations by avoiding sharp edges of the dielectric; by tapering it at the cable ends.

I agree with the author of the paper that probably the phenomena leading to the corona in air are of the same nature as the deterioration of the solid dielectric by overstrain. The corona, my experience led me to believe, also is a disruptive effect and consists of innumerable minute streamers, the same as the pin points which perforate the solid dielectrics, the difference being merely that with the air those pin holes heal again, but they do not heal in the solid dielectric.

In discussing the break down of a dielectric by an overstrain we generally assume, and I believe correctly, that there is a finite dielectric strength to air, to solid dielectrics, etc. Usually the break down is explained by assuming that if at any point in the electrostatic field, the electrostatic gradient exceeds the dielectric strength of the material, a break down occurs at that point, and then may spread further if the conditions are favorable. Since on conducting wires the maximum potential grading is at the surface of the wire, the break down should occur at the wire surface as soon as the electrostatic gradient at this surface exceeds the dielectric strength of air. Calculating, however, the electrostatic gradient at the conductor surface from the voltage at which corona formation begins—and this voltage can be determined with great accuracy—we find that this electrostatic gradient is not constant but increases very greatly with decreasing size of wires. This has been explained by assuming a layer of condensed air on the surface of the conductor. I believe I am responsible for this explanation which I gave seventeen years ago in a paper on the dielectric strength of air, and I am the more sorry to say that investigations which we made during the last months have led me to doubt this explanation.

In the pursuit of a very extensive investigation of the phenomena of the electrostatic field in air and other dielectrics —of which we may be able to communicate some of the results at the next annual convention—I began to question whether the break down in the electrostatic field does take place as soon as the potential gradient exceeds the breakdown strength of the dielectric at any point. The results rather led me to suspect a different law. "In an electrostatic field a break down of the dielectric occurs as soon as the potential gradient has exceeded the dielectric strength of the material within a volume sufficiently large that the discharge current within that volume has an appreciable value. Corona thus forms at a conductor not as soon as the dielectric strength is exceeded at the surface, but only after the potential gradient has exceeded the break-down strength up to a certain distance from the conductor which is sufficiently large that the current charging and discharging the volume of air within this distance has an appreciable, though minute value."

This explains the increase of the potential gradient with a small conductor and also agrees with other phenomena which apparently contradict the assumption of the constant break-down gradient of dielectrics.

When there is an explanation suggested as the result of experimental evidence, it is always well for a moment to set aside the experimental results and reason what we should expect from the known properties of things.

When a break down occurs in a dielectric it means that in that broken down space a current flows. Now what are laws of current flow in air or other gases or in those materials which are used as insulating materials, in solid dielectrics. We find that the effective resistance is not a constant but is a function of the current density and has an enormous negative coefficient; that is, the resistance increases enormously with decreasing current density, approaching or tending towards infinity for zero current.

Now you see what could follow from this. If the break-down strength is exceeded at one point or a very small volume, the dielectric may be stressed beyond breakdown, but there can not yet be a current flow, since that current would be so small that the resistance of the material is too high, that is, gives a higher potential consumption than the potential gradient available in that space. You must first break down a sufficiently large volume to bring the resistance of the dielectric down sufficiently to pass the current. Thus the very phenomena which I outlined above should be expected from the laws of gas conduction and from the laws of the conduction of those dielectrics which are used as insulating material.

To conclude, I desire to congratulate the author, not only on the very important results which he has communicated to us, but also on the very scientific manner in which he has given the results of his investigation by stating the experimental facts, as such and without detracting from their value by giving instead of the facts their interpretation by some prevailing theory or speculative hypothesis.

C. O. Mailloux: The remarks made by Mr. Thomas caused me to recollect some interesting experiments which I made thirteen years ago. I had gone to Vienna to investigate a certain insulating compound. I utilized there the facilities placed at my disposal by Professor Grau of the Technical High School of Vienna. Together, we made some experiments for the purpose of demonstrating and determining approximately, (which was all that was possible, with the crude methods and knowledge at that time available to us), the relative resistance to puncture of different insulating substances. The particular compound which I was investigating specially was a mixture intended to replace and to constitute a substitute for gutta-percha. Hence I naturally compared it with gutta-percha. Inasmuch as that compound was intended to be used largely for making cables, I also compared it with several other compounds which were then on the market, notably the " wax " compounds used by Siemens & Halske for high-tension cable insulation. We made some experiments by taking sample sheets of the material of varying thickness, from a half a millimeter to seven or eight or even ten millimeters thick, and maybe from ten to fifteen centimeters square. We subjected these samples to puncture tests by placing them in the spark-gap of an electrostatic machine. As nearly as we could estimate, with the facilities we had, we were able to raise the pressure to as high as 50,000 or 60,000 volts, and to reduce it to 10,000 or 15,000.

The usual method of procedure was to lay the plate of material flat on a plate of metal forming one electrode or sometimes on a point, that is, allowing it to rest on one of the electrodes. We used vertical electrodes of various forms, some of the needle-point variety, some of the " knob " variety. We placed the electrodes near to or far away from the sample, according to the case, but always had the conditions the same for each set of experiments. By raising the voltage we could increase the stress; and, usually we would keep up the stress until puncture took place or until we found that the voltage was insufficient for the particular case. It should be stated that the pressure used was usually sufficient to cause brush discharge and sparking discharges over and around the edges of the sample. Now, I observed repeatedly that before puncture took place in any of the waxy materials, or in any compound, (*i.e.*, any " made-up " compound) there was always a slight preliminary *pitting* produced at the point where the puncture was to occur. After that pitting action began the puncture would occur generally (perhaps invariably), in a very short time. The idea occurred to me that there must be two actions here—a mechanical action, and a thermic action. So we tried the experiment of stopping the test before the puncture took place. First, by a series of experiments we determined that a puncture would take place in so many seconds or minutes, as the case night be, with the application of a certain voltage; *i.e.*, we had found out what pressure was requisite and how long it must be kept up in order to produce punctures. I came to the conclusion that the puncture took place at a certain point which was first *heated* either by the passing of a very weak current resulting from dielectric hysteresis or by some slight conduction-current actually passing through the plate, which had the effect of heating it slightly. The moment it heated, the resistance decreased very greatly as is the case with all insulating materials of that kind, thereby allowing a still greater amount of current to pass through. Suspicious that this might be the explanation, we tried the experiment of removing the stress. After subjecting the plate to a high voltage for a certain short time, we would stop just short of puncture. We did that many times, and we noticed that if we allowed the plate to cool it would eventually recover very nearly if not all of its power to resist to puncture. Of course whenever pitting had already occurred the total thickness of the sample was diminished at the pitted point and consequently less pressure and less time were required to produce puncture. This led me to believe that the puncture took place, when it did occur, as the result of a lowering of the resistance which allowed the dielectric resistance to fall to such a point that actual conduction took the place of electrostatic conduction.

Another point which I wish to call attention to is that, in Europe, at least, there is a quantitative estimate or measure made of the difference in the breaking down ability of alternating current and direct current. At the Marseilles Electrical Congress in 1908 the question came up before the Section at which I presided, and, at the request of one of the members, I appointed a committee to interview the various cable manufacturers represented at the exposition or at the congress and ascertain from them what difference, if any, they would make in the margin of allowable potential if the current used were a direct or continuous current instead of an alternating current. One of the reasons which led to the discussion of this subject and to the appointment of the committee was an interesting exhibit made at Marseilles in which an alternating current of very high potential, something like 100,000 volts, was commutated and then applied to a cable. I believe the manufacturers dared anybody else to try such a voltage on their cables and especially to try it in the alternating-current form. The next day after the committee was appointed it reported at the meeting of the session; and my recollection is that every cable manufacturer had stated that a much higher voltage would be allowed if the voltage were "direct-current." The figures are probably to be found in the official report of the discussions before that section (*i.e.*, Section II) of the Congress. My recollection is that the figures ranged from one and one-half to two or more times the voltage. In other words, the cable manufacturers were willing to allow from fifty per cent to one hundred and fifty per cent more voltage in the form of direct current than of alternating current. The discussion of the report of the committee led to an expression of opinion by several members familiar with this subject, to the effect that the strain produced by an alternating e.m.f. is at least proportional to the maximum value of the potential difference during each cycle, if not greater.

Tracy D. Waring: In the development of any theory it is well, and generally necessary, to begin with the simplest assumptions. The simplest theory of graded cables assumes that, for a given insulating material, we may assign to it a *definite* resistivity and a *definite* electric permitivity, or to speak in terms more familiar in the practice of cable engineering, the theory of graded cables requires that we know, for each insulating material, the value of those electric quantities with which the ideas of insulation resistance and of electrostatic capacity of cables are associated.

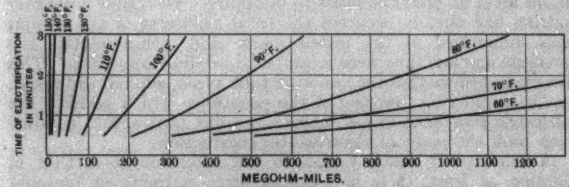

FIG. 1.—Showing change of insulation resistance with change in duration of electrification for various temperatures. Based on the assumption that under constant voltage the leakage current is a measure of the insulation conductance.

Now it is well known that these qualities, for a definite insulating material, as determined by the customary commercial methods of testing, are anything but constant. The megohm-miles and the microfarads per mile for a given cable vary with the time of electrification and with the temperature.

Figs. 1, 2, 3 and 4, derived from tests on rubber insulated wire may be taken as typical of the change of insulation resistance and of electrostatic capacity with change of temperature, and different durations of electrification or charging.

It is worth while to consider how far the electrical qualities thus determined are applicable to the theory of grading, both for direct current and for alternating current voltages.

Under constant voltage the insulation resistance increases very considerably with the duration of electrification, (see Fig. 1) but at a different rate for different insulating materials, so that for a graded cable, made with layers of different materials, the potential gradient from conductor to sheath cannot remain unchanged after the voltage is applied and in fact it may be hours before a steady state sets in. Evidently also, under direct current voltage, the voltage gradient changes with alterations of temperature; for the insulation resistance of different materials have different temperature coefficients, so that, for a graded cable subjected to direct-current voltage, the voltage gradient in the various layers would be different at different temperatures.

Under present industrial conditions, however, the chief practical interest pertains to grading for alternating voltages, and in view of the curves in Fig. 1. it may well be asked whether the insulation resistivity under alternating voltage is of a magnitude any where near that usually ascribed to insulating materials, such, for instance, as the figures given in the paragraph following equation (9) for rubber and for paper.

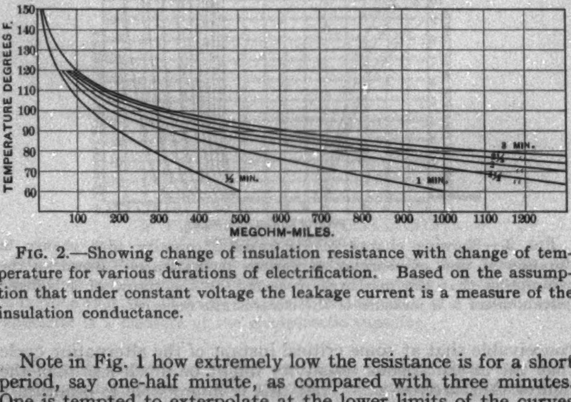

FIG. 2.—Showing change of insulation resistance with change of temperature for various durations of electrification. Based on the assumption that under constant voltage the leakage current is a measure of the insulation conductance.

Note in Fig. 1 how extremely low the resistance is for a short period, say one-half minute, as compared with three minutes. One is tempted to exterpolate at the lower limits of the curves and assume that, for very short intervals of electrification, say for one-half a cycle of alternating current, the resistivity of the dielectric would be extremely low, so low in fact as to make the resistivity and not the electric permitivity the determining factor in the voltage distribution in the dielectric, and thus to contradict the statement, "that in ordinary cases the conductance is negligible."

Exterpolation is, however, extremely dangerous and definite experimental figures for resistivity for short periods of electrification should be demanded to decide this question. A limiting minimum value for the "ohmic" resistance of a cable under alternating-current voltage may be obtained from a consideration of the dielectric energy losses under known voltage and charging current. It is to be borne in mind, however, that the figure thus arrived at is simply the equivalent effective resistance and is not the true resistance, for the greater part of the dielectric losses are hysteresis losses and not generally attributed to the true resistance. The true effective "ohmic" resistance cannot, however, exceed the figure thus obtained. Calculations of specific cases made on this basis generally show that the effective equivalent resistivity, although hundreds of times lower than the "ohmic" resistivity at one minute electrification, is still so high as to indicate that the resistivity is not the determining factor for the voltage gradient under ordinary frequencies.

Although (in view of dielectric hysteresis) the true effective ohmic resistivity cannot exceed the figure thus calculated, it is conceivable that at some critical instant of the alternating cycle that the instantaneous resistivity might be much less than the figures thus arrived at. That this is improbable is beautifully shown in the oscillograph records presented by Hōchstādter[1] and as pointed out by him it is an extremely interesting fact that, in spite of dielectric losses during the cycle, that at the exact instant when the applied voltage was at its maximum the current was zero, from which it may be concluded that, at the instant of greatest danger to breakdown, it is not the resistivity of the insulation which determines the voltage gradient.

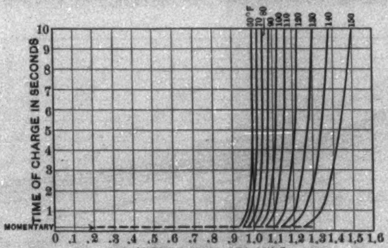

FIG. 3.—Showing change of electrostatic capacity with change in duration of time of charging at various temperatures. Based on the assumption that the discharge measured by the throw of a ballistic galvanometer is a measure of the electrostatic capacity.

I think it may be said, however, that we know very little of the true resistivity of dielectrics under extremely short periods of electrification, the displacement current and the leakage current being difficult to differentiate, and I believe the dielectric losses under the same condition have never been analyzed experimentally into conduction losses and hysteresis losses.

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[1] *Elek. Zeit.* May 12–19–26 and June 2, 1910. The results referred to were obtained on impregnated paper insulated cables. Tests on other materials might lead to different conclusions.

Consider next the electrostatic capacity tests as shown in Figs. 3 and 4. The length of time designated as "momentary" refers to the mere tapping of the charging key thus charging the cable for a brief period and immediately discharging it through a ballistic galvanometer.

The capacity thus measured might be expected to give a suitable figure for calculating the charging current under alternating voltage. It has often been remarked however that the capacity calculated from the mean effective charging current and voltage does not accord with the capacity measured ballistically. It has been shown experimentally by Höchstädter, from oscillograph records of tests on paper cables, that the discrepancy disappears if the capacity be calculated from the maximum instantaneous value of the voltage and from the charge in the cable at that instant. This agreement only holds, however, for capacities measured ballistically at rather low temperatures. As a matter of fact the experiments just referred to showed that the electrostatic capacity measured by the charging current is constant, and independent of the temperature. That is, it may be inferred that the electric permittivity is a true constant independent of the temperature and does not change with the temperature at all in the way that is indicated by the ballistic capacity tests.

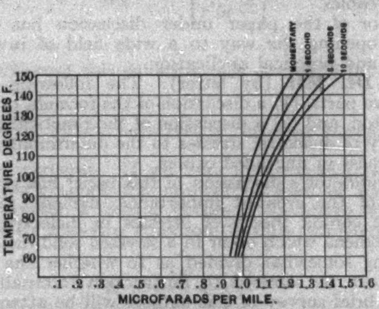

FIG. 4.—Showing change of electrostatic capacity with change of temperature for various durations of time of charging. Based on the assumption that the discharge measured by the throw of a ballistic galvanometer is a measure of the electrostatic capacity.

The bearing of this point on the grading of cable is evident since it has commonly been supposed that the dielectric permittivity varied with the temperature and thus, for instance, an ungraded cable, when heavily loaded would become automatically equivalent to a graded one, since the temperature next the conductor would be higher than at the sheath; but if electric permitivity is independent of temperature this would not be the case, and in any cable the voltage gradient in the insulation, under alternating voltage, would not be influenced by temperature. There can be no doubt that the electrostatic capacity of a cable as measured ballistically is open to grave possibilities of error on account of absorbed charge and by change of the absorption and insulation resistance with the temperature. In any event it is evident, from these and other considerations, that the so-called constants of resistivity and electric permitivity as usually determined in commercial cable testing are, in general, not to be taken as adequate for determining the actual voltage gradient in cables.

The author of the paper under discussion has admirably assisted in opening the way to a wide field of investigation, speculation and practical application.

Wm. A. Del Mar (by letter): The following comments consist of two parts, (1) a discussion of the formula presented by Mr. Middleton, and (2) a discussion of the practical application of the theory of dielectric stresses to the determination of insulation thickness in ungraded cables.

1. Mr. Middleton's discussion of this paper has given rise to a question of the greatest importance, namely, the relation between the corona theory of stresses in dielectrics and the actual phenomena which occur in a stressed solid dielectric, and opinion being somewhat divided as to whether the insulation of a cable can be stressed to destruction internally without puncture, a brief survey of this subject will be attempted.

The author of the paper under discussion gives the following well known formula for the relation between the dielectric stress, the difference of potentials between conductor and sheath and the dimensions of the cable.

$$F = \frac{V}{\rho \ln \frac{R}{r}} \tag{1}$$

where R = outer radius of insulation.
r = radius of conductor.
ρ = distance from axis of wire to point where dielectric stress is F, when the volts between wire and sheath equal V.

This formula is based upon the assumption that the lines of electrostatic induction extend radially between the conductor and sheath and that therefore their density, or, in other words, the dielectric stress, is the greatest at the surface of the conductor, so that K, the maximum value of F is given by

$$K = \frac{V}{r \ln \frac{R}{r}} \tag{2}$$

If we keep the applied voltage and outside diameter of the insulation constant and vary the radius of the wire, we obtain

$$\frac{d K}{d r} = V \frac{\left(1 - \ln \frac{R}{r}\right)}{\left(r \ln \frac{R}{r}\right)^2} \tag{3}$$

An inspection of this equation tells us that if $\ln \frac{R}{r}$ is greater than one, $\frac{d K}{d r}$ will be negative, or, in other words, K will decrease as r increases. If we take into consideration the fact that $K = 4 \pi \epsilon$ times the number of lines of induction per square centimeter, a mental picture of the above relations may be obtained by resolving equation (2) into two parts as follows:

$$K = \frac{V}{2 \ln \frac{R}{r}} \times \frac{2}{r} \tag{4}$$

and dividing by $4 \pi \epsilon$ to obtain N the number of lines of induction per sq. centimeter at the surface of the conductor. Thus

$$N = \frac{V}{2 \ln \frac{R}{r}} \times \frac{2}{r} \times \frac{1}{4 \pi \epsilon}$$

$$= \frac{1}{2 \ln \frac{R}{r}} \times \frac{V}{\epsilon} \times \frac{1}{2 \pi r} \tag{5}$$

In this equation the first item represents the capacity of the condenser formed by the conductor and sheath; the product of the first and second terms represents the total number of lines of induction between the conductor and sheath; the third term is reciprocal of the area per unit length of the conductor; and the product of the three terms, the number of lines of induction per sq. centimeter of conductor surface.

In Fig. A, curve *B* gives the relation between the total number of lines of induction between conductor and sheath and the conductor radius; curve *C* is the reciprocal of the conductor surface per unit length, and curve *A* is the number of lines of induction per unit area at the conductor surface, these curves being obtained from equation (5) as described above. It will be noted from Fig. *A* that curve *A* first drops owing to the slowness of the flux increase as compared with the rapidity of its surface attenuation and then rises again owing to the reversal of these conditions. There is therefore a point of minimum flux density and therefore of minimum dielectric stress and this occurs when r is $\frac{1}{2.72}$ of R.

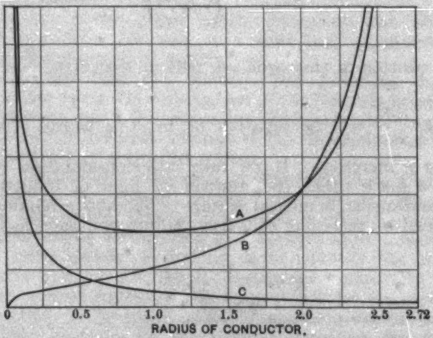

FIG. A.—Curve A: Dielectric stress, or lines of electrostatic induction per unit area. Curve B: Totol number of lines of electrostatic induction or condenser capacity. Curve C: Reciprocal of surface area per unit length

The ordinates of these curves may be regarded either as flux densities or dielectric stresses, these quantities being related by a constant ratio. The ordinates are therefore given without any specified scale in order that the curves may be used for either of these quantities.

This graphical exposition is given in order to emphasize the physical meaning of the equations under discussion. Thus in the case of cables in which $\frac{R}{r}$ is greater than 2.72 we see from curve *A*, Fig. A, that if the conductor were to grow in diameter, the dielectric stress at its surface would decrease until its diameter became $\frac{1}{2.72}$ of the outside diameter of the insulation, after which $\frac{R}{r}$ being no longer greater than 2.72 the stress would increase. If instead of the conductor growing in diameter, the dielectric at its surface were to break down, the effect would be the same. The stress in the uninjured dielectric where it meets the injured part would decrease until the diameter of the injured part equalled $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would decrease. If, therefore, the applied voltage is just sufficient to break down the layer of insulation nearest the conductors, the next layers of insulation will not necessarily break down, as the virtual increase of conductor diameter due to the breakdown of the layers will have eased the stress to a safe value. Hence in such a cable a partial internal distintegration of dielectric should be possible without a complete puncture.

Considering the case of cables in which $\frac{R}{r}$ is less than 2.72 so that K increases as r increases, a similar line of reasoning leads to the conclusion that if one layer of insulation is disrupted the next layer becomes more greatly stressed than the first and so on to the outside of the insulation, with the net result that the insulation is completely disrupted from the conductor to sheath.

Returning now to the consideration of cables wherein $\frac{R}{r}$ is greater than 2.72 and assuming that the disintegration of inner layers is unobjectionable if the outer layers remain intact, we come to the conclusion that the outside diameter of the insulation is a constant entirely independent of the size of conductor and dependent only on the applied voltage. Referring to equation (2) assume that $\frac{R}{r} = 2.72$ so that $r = \frac{R}{2.72}$ and $ln\ \frac{R}{r}$ becomes unity. Then

$$K = \frac{2.72\ V}{R}, \text{ or } R = \frac{2.72\ V}{K} \tag{6}$$

This is what Mr. W. I. Middleton's formula reduces to, when his wire diameter d is replaced by $\frac{D}{2.72}$ as he requires to be done.

Now it will be observed that the establishment of this formula depends upon the admission that the inner layers of insulation are broken down without injury to the outer layers; what, therefore, does Mr. Middleton mean by saying that "as far as Professor Russel's hypothesis that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excess voltage in either rubber or cambric insulation." Granting that the insulation neither chars nor breaks down visibly it would be interesting to know, first, what kind of change actually occurred in the inner layers of those cables which he tested to check the accuracy of his formula, and second, is there any physical meaning to his formula if it does not assume the partial internal disintegration of the dielectric.

Without wishing in any way to deprecate the value of Mr. Middleton's work or question its originality, I must venture to observe that Professor Alexander Russel gives this formula in his paper read November 7, 1907, before the Institution of Electrical Engineers (JOURNAL I. E. E., Vol. 40, p. 15, line 12) but that Mr. Middleton deserves our thanks for calling attention to its practical value, especially to the fact that for a given voltage the outside diameter is a constant while the copper diameter is a reducible quantity.

2. The application of the theory of potential gradient to the practical design of ungraded cables is a matter of great importance to which we will now turn our attention.

The equation (2) may be reduced, for practical purposes, to the form

$$K = \frac{0.434\ V}{r \log \left(\frac{t+r}{r}\right)}$$

where the logarithm is to the base ten, and t represents the thickness of insulation. This equation may be used to calculate the thickness of insulation required to properly insulate a cylindrical wire of known radius. If, however, the wire is not cylindrical but consists of a strand of several wires, the formula becomes more complicated owing to the irregular distribution of the lines of induction about the wires composing the strand. It has been shown by Professor Levi-Civita that stranding has the effect of increasing the stress by a factor which varies from 1.23 for thick insulation, to 1.46 for thin insulation, an average value being 1.345, so that

$$K = \frac{0.585\ V}{\left(r \log \frac{t+r}{r}\right)} \tag{8}$$

The thickness of insulation calculated by the above formulæ is inadequate because there is always a certain amount of insulation which is not effective as such. In practical cable work, it is found necessary to add an extra thickness to make up for this inevitable deficiency. The useless thickness may be analyzed as follows.

1. Eccentricity of insulation about the wire making the insulation dielectrically stronger on one side of the wire than on the other, the excess on one side over that of the other being useless.

2. Insulation in immediate proximity to the wire being likely to be abraided in bending, etc., is rendered useless.

3. Insulation next to taping being likely to contain depressions due to crinkling of tape is rendered useless.

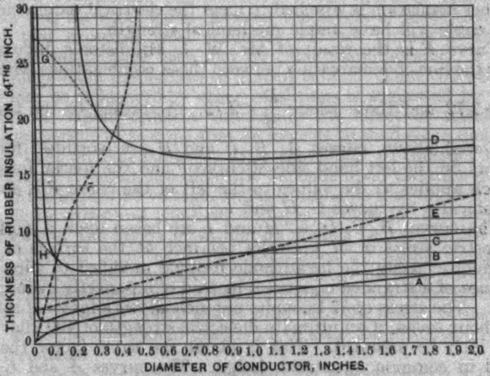

FIG. B

4. When cable is bent, the insulation on the outside of the bend is reduced. Hence, a cable when straight should have an excess of insulation in order that when bent, it may have just sufficient. This excess must, of course, be figured as useless in calculating insulation thickness on a straight conductor.

This "error thickness" as we may call the total of these quantities is a function of the size of conductor and has to be determined by experience. Curve *A* in Fig. B represents what the writer considers to be about the practical magnitude of the error thickness for rubber insulated cable.

Applying the logarithmic formula to the case of a wire insulated with rubber compound for 550 volts alternating current (or say 775 volts direct current) we obtain curve *B*, by assuming a working stress of $K = 57$ kilovolts per inch and plotting the thickness obtained by calculation, upon curve A as base so that curve B represents the electrical thickness plus the error thickness. The thickness of insulation thus obtained is, however, not sufficient to meet the requirements of practical work owing to the severe mechanical stresses to which wires are subjected. It is therefore necessary to add insulation until the amount shown on curve E is reached.

Proceeding in the same way for 2300-volt cables, curve C is obtained, part of which is below and part above curve E. With wires for this voltage the thickness of insulation is therefore partly determined by mechanical and partly by electrical considerations.

Curve D is obtained in the same way for 6700-volt cables, this being used for 11,000 volts three-phase. This curve is entirely above curve E, showing that in this case, if sufficient rubber insulation is supplied to meet the electrical requirements, the cable will have ample mechanical strength.

Curve F is the result of Mr. W. I. Middleton's discussion. It is the line of demarcation between those combinations wherein $\frac{D}{d} > 2.72$ and those where $\frac{D}{d} < 2.72$. According to the theory reviewed above, curves A, B, C and D are worthless for all points on the left hand side of curve F and the special formula which applies to the values to the left of the curve F is shown graphically by curves G, H and I.

The curves B, C, D, G, H and I are based upon a working dielectric stress of 57 kilovolts per inch at the surface of the conductor, using the logarithmic formula modified to allow for the use of a stranded conductor instead of a perfectly cylindrical one. The stress of 57 kilovolts per inch allows a factor of safety of about seven, if an ultimate dielectric strength of 400 kilovolts per inch be assumed. This is about the same factor that is used in common structural design. The curves A and E are taken (by permission of the D. Van Nostrand Co.) from tables in Appendix III of the present writer's " Electric Power Conductors."

Engineers have hitherto avoided the use of small wires with heavy insulation because they cost more than larger wires with less insulation, and it is a curious fact that the curve F, which as explained above, has a purely physical basis, also represents, to a fair degree of approximation the limit of the commercial application of the old logarithmic law, *i.e.*, those portions of the curves B, C and D which are replaced by curves I, H and G respectively give thicknesses of rubber of insulation which are commercially impracticable. The curves G, H and I, may, on the contrary, give commercially practicable thicknesses of insulation and are therefore of more than academic interest, but at present prices ($0.14 per lb. for copper and $2.00 per lb. for rubber) it is cheaper to use copper up to a diameter $\frac{1}{2.72}$ of the outside diameter than to use rubber compound on the expectation of its being disintegrated. In addition to this, the extra copper adds to the carrying capacity and to the scrap value, so that it is usually better engineering to use it instead of rubber.

The practical points brought out above in considering the thickness of ungraded insulation suggest that in designing graded insulation, the theory set forth by Mr. Osborne may have to be materially modified in practical details before it can be adopted by the cable manufacturers.

H. S. Osborne: It has been pointed out in several of the discussions that the design curves which are given in the paper will be modified by mechanical considerations and by manufacturing conditions. The necessity, which Professor Kennelly points out, for good joints between the layers of insulation, in order that excessive local gradients will not appear at those joints, seems to have been met by cable manufacturers, if one may judge from the success of graded cables. That the design may also be influenced by other conditions is suggested by Dr. Steinmetz, whose remarks concerning the effect of transient voltages permit us to hope that he intends to shed some quantitative light on that subject. It is customary to consider that the electric strength of a dielectric depends upon the time duration of the impressed voltage; and it is probable that in designing a cable to withstand transient voltages, values for the electric strengths of the layers of insulation should be used which are quite different from the values determined by ordinary means. It does not appear, however, that the energy necessary to complete the breakdown of a dielectric, after it has been stressed up to the breaking point, would enter into the design of insulation, since the aim should usually be to keep the insulation from all overstress.

Mr. Rhodes has pointed out that the voltage which a cable can withstand is not necessarily the criterion by which it will be judged, and has very clearly shown what advantage may be expected from grading a cable when the aim is for a maximum safe kilowatt capacity per duct. In most cases the aim in designing a cable is for a minimum cost with fixed voltage and current-carrying requirements, and the design is therefore fixed by a consideration of relative costs, of which no analysis is attempted in this paper. In this connection it is interesting to hear from Mr. Middleton that cable manufacturers find grading to be of value for voltages above 15 kv., though theoretically the advantage to be gained depends, not on the voltage for which the cable is designed, but upon the ratio of that voltage to the diameter of the conductor.

It would seem to be a matter for personal preference to decide whether one shall express the stress on the dielectric in terms of the electric flux density, as Mr. Fechheimer suggests, or in terms of the potential gradient. Personally, I prefer to consider the potential gradient to be the measure of the electric stress to which the dielectric is subjected, and the flux density to be the measure of the resulting strain. It is advantageous to deal with what is, from this point of view, the stress, rather than to deal with the strain, because a potential gradient is more easily measured than a flux density, and the electric strengths of dielectrics are ordinarily given in terms of potential gradient. The characteristic of a dielectric which is of primary interest is its volt-resisting ability, rather than its ability to transmit electric flux.

In remarking that "electric strengths are limited at present, in the manufacture of cables, to a very few values," the author did not mean to convey the idea that electric strengths are limited to a single value. The criterion given by Mr. Fechheimer for the ideal grading of cables is expressed in equation 5 of the paper.

Mr. Rhodes and Mr. Waring have discussed the effect of a temperature gradient in the insulation of a cable on the distribution of the electric stress. Mr. Höchstädter, to whose recent researches Mr. Waring refers, found that not only the effective capacity of an impregnated paper cable, but also what he calls the "true" capacity of the cable remained sensibly constant for temperatures between 20 deg. and 60 deg. cent., though the "static" capacity, as measured by a ballistic galvanometer, increased largely. It seems probable, then, that the effect of temperature gradient in equalizing the stress in a cable is very small, if it is indeed appreciable.

The conclusion in the paper with regard to the nature of partial breakdown in solids seems to be generally acceptable; Dr. Steinmetz, indeed, considers it to be a fairly well known fact. It is so simple and obvious an explanation of experimental results that it would be remarkable if some such idea had not been in the minds of some engineers, but it has not before, as far as I am aware, been expressed in public discussions of this subject.

In describing in terms of the electron theory the experiments reported in the paper, Professor Whitehead seems to be mistaken with regard to one of the experimental facts. The experiments in no case indicated that the dielectric could be overstressed without breakdown, but in each case the dielectric broke down when its electric strength was exceeded. Dr. Steinmetz's experiments lead him to conclude, however, that under certain circumstances the electric strength of a dielectric may be exceeded without causing any change in the material.

Mr. Thomas describes the experimental results in terms of local heating. In adopting this point of view one should bear in mind the fact that the "heating" seems to be of a different sort from that due to ohmic resistance, and is accompanied by a disintegration of the material at the point of puncture, however small may be the current which is allowed to flow. In the cases in which the authors have observed the melting and pitting of a dielectric before puncture which was remarked by Mr. Mailloux in substances of low melting point, the heating has evidently been caused by the brush discharge in the air around the electrodes.

Mr. Fisher and Mr. Thomas have both suggested that the experimental results observed would be different, or at least less pronounced, were materials other than glass and rubber used for the experiments. This may well be, and it is to be hoped that experiments will soon be forthcoming which will more completely determine the behavior of overstressed dielectrics. It does not seem probable that the *character* of the partial breakdown was due to the presence of flaws in, or to the lack of homogeneity of the material, as suggested by Professor Whitehead and Mr. Franklin, though doubtless the voltage at which that breakdown occurred was influenced by the lack of absolute homogeneity. The possible effect of a layer of air, suggested by Professor Kennelly and Mr. Thomas, was obviated after the earliest experiments by the use of a liquid dielectric between the rubber and the glass tube.

The curves marked *C* in Figs. 10 and 12 were intended only to give a very rough idea of the magnitude of charging current which might be expected in those cases of partial breakdown. As the resistance to the passage of current along the lines of incipient disruption is probably low, the change in the phase angle of the current which is suggested by Mr. Atkinson does not necessarily occur, and it was therefore assumed in computing curves *C* that the phase angle of the current remained unchanged. The increase in " static " capacity which was noted by Professor Kennelly in the testing of some rubber cable would seem to be most readily explained by a rise in the temperature of the dielectric.

It is very interesting to learn from Mr. Middleton that the formula which assumes the complete breakdown of the overstressed zone of a thick wall of insulation gives results which are satisfactory in practice. This fact seems to indicate that in the cases with which Mr. Middleton deals the potential gradient remaining in the partially disrupted zone of insulation approximately compensates for the excessive stresses introduced by the needlepoints.

The inconsistency of the present nomenclature concerning capacity prompts one to wish that the term *permittivity*, which Mr. Waring uses, might come into general use. If Heaviside's rational units were adopted the nomenclature could be simplified in the way indicated in the following. For the sake of simplicity, the case here considered is that of a parallel plate condenser, *A* representing the effective area of the plates and *t* the thickness of the dielectric:

Quantity	Present name	Rational name
$\frac{\epsilon A}{t}$	Capacity	Permittance
ϵ	Specific capacity	Permittancy or permittivity

There seems to be little hope of the immediate adoption of a rational system of electric units, but with our present system of units the capacity nomenclature could be made consistent with the rest of electrical nomenclature. For example, the following terms have been suggested:

Quantity	Present name	Consistent name
$\frac{\epsilon A}{4 \pi t}$	Capacity	Capacitance
$\frac{\epsilon}{4 \pi}$	(?)	Capacity, or capacitivity
ϵ	Specific capacity	Permittivity

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INTERPOLES IN SYNCHRONOUS CONVERTERS

BY B. G. LAMME AND F. D. NEWBURY

Synchronous converters with interpoles have been used but little in this country, but they have been built to some extent in England and on the continent of Europe, principally by companies which are either directly connected with or very closely allied to the companies which have manufactured the great bulk of the converter apparatus installed in this country. Considering that interpole generators and motors came into extensive use in this country at about the same time as in Europe, the question would naturally be raised why interpole converters have not come into similarly extensive use, especially as the principal designers of converters in this country are in direct touch with the designers of the commutating pole converters in Europe. The reply might be that the introduction of any new type of apparatus is a relatively slow process; but, on the other hand, interpoles on direct current generators and motors came into general use in a relatively short time, especially so in railway motors. This indicates that there has been a more or less pressing need for interpoles in certain classes of apparatus and the greater the need for the change the quicker was the change made. Any important change in design or type must be justified by engineering and commercial reasons, such as improved performance greater economy, or lower cost. In the railway motor, placed under the car, and more or less inaccessible, improved operation at the brushes and commutator, when equipped with interpoles, represented a pressing reason for the change in type, although the cost and efficiency were not appreciably changed. In the direct-current generator with the modern tendency toward higher speeds with lower cost, the interpoles represented a practical necessity. This has been recognized for several years and the change to the interpole type has been made as rapidly as circumstances will permit. Also, in variable-speed direct-current motors interpoles have been in general use for a number of years, simply because the interpoles represent a very definite improvement in a number of ways.

New types of apparatus should only be introduced where they represent some distinct improvement or advance over existing types. Where a new type does not represent such improvement and is simply introduced to gratify a personal whim of the purchaser, or desire on the part of a manufacturing company to produce something different from other companies, the new apparatus, as a rule, will not advance quickly into public favor since there is no real necessity for it.

It is therefore a question whether the slowness in the introduction of interpoles in synchronous converters is due to lack of sufficient advantages, or American engineers do not sufficiently appreciate their advantages. There appears to be room for wide differences in opinion on this subject. The synchronous converter and the direct-current generator are two quite different machines, in their characteristics, and no one can say off hand, that interpoles will give the same results in both. In the following is given a partial analysis of the conditions occurring in the two classes of machines, which will indicate wherein interpoles are of greater advantage on direct-current generators than on converters.

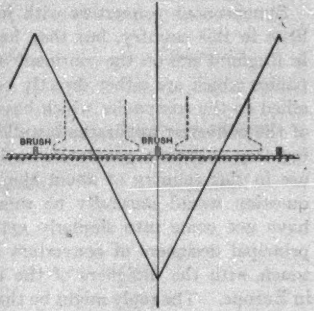


FIG. 1

Taking up first, the direct current generator, it may be considered as containing two sets of magnetizing coils, namely, the armature and the field windings. Considering the armature winding alone, the magnetomotive force of the armature winding has zero values at points midway between two adjacent brush arms or points of collection of current and rises at a uniform rate to the point of the winding which is in contact with the brushes. This is illustrated in Fig. 1. Therefore the armature winding has its maximum magnetizing effect or magnetomotive force at that part of the core surface where the winding is directly in contact with the brushes. However, the magnetic flux set up by the armature winding will not necessarily be a maximum at this point, as this depends upon the arrangement of the magnetic or other material surrounding the armature. If this point occurs midway between two field poles, then, while the magnetizing effect is greatest at this point, the presence of a large air-gap at this same point may mean a relatively small magnetic flux, while a much higher flux may be set up by the armature winding at the edges of the adjacent field poles. In the usual direct-current generator construction without interpoles, the position of commutation is almost midway between two adjacent poles and therefore the point of maximum magnetomotive force of the armature is also practically midway between poles. The absence of good magnetic material over the armature at this point serves to lessen the magnetic flux due to the armature magnetizing effect, but even with the best possible proportions there will necessarily be a slight magnetic flux set up at this point. While this field is usually of small value, yet unfortunately it is of such a polarity as to have a harmful effect on the commutation of the machine. During the operation of commutation, the coil which is being commutated has its two terminals short-circuited by the brushes. If this short circuited coil at this moment is moving across a magnetic flux or field, it will have an e.m.f. set up in it which will tend to cause a local or short circuit current to flow. Such a current is set up by the flux due to the armature magnetomotive force described above and unfortunately this current flows in such a way as to give the same effect as an increased external or working current to be reversed as the coil passes from under the brush. In other words, the e.m.f. set up in the short circuited coil by the above field adds to the e.m.f. of self induction in the coil due to the reversal of the working current.

Another cause of difficulty in the commutation of a direct current machine is the self induction of the armature coils as they individually have the current reversed in them in passing from one side of the brush to the other. Each coil has a local magnetic field around itself, set up by current in itself and its neighboring coils. The value of this local magnetic field depends upon the arrangement of the winding, the disposition of the magnetic structure around the coil, the ampere turns, etc. During the act of commutation, that part of the local field due to the coil which is being commutated must be reversed in direction. It is therefore desirable to make the local field due to any individual coil as small as possible. This means that the number of turns per coil should be as low as possible, the amperes per coil also should be as small as possible, while the magnetic conditions surrounding the coil should be such as to give the highest reluctance. By the proper arrangement of the various parts, it is usually found that the e.m.f. of self induction, due to the reversal of the coil passing under the brush, can be made of comparatively small value so that, if no other conditions interfere, good commutation could be obtained under practically all commercial operating conditions. However, the magnetic field between the poles set up by the armature magnetomotive force as a whole, as described above, adds very greatly to the difficulties of commutation. If the armature magnetomotive force, or the field due to it, could be suppressed, then one of the principal limitations in the design and operation of direct-current generators would be removed, and the commutation limits would be greatly extended. Or, better still, if a magnetic flux in the reverse direction were established at the point of commutation, then the e.m.f. set up by this would be in opposition to the e.m.f. of self induction of the commutated coil and would actually assist in the commutation.

This latter is what is accomplished by interpoles. When these are used the brushes on the commutator are so placed that the short circuited or commutated coils are directly under the interpole. Consequently, the maximum magnetomotive force of the armature is in exact opposition to that of the interpoles. Therefore, the total ampere turns on the interpoles should be equal to the total ampere turns on the armature in order to produce zero magnetic flux under the interpole or at the point of commutation. But, for best conditions there should not be zero field, but a slight field in the opposite direction from that which the armature winding alone would produce. Therefore, the magnetomotive force of the interpole must be greater than that of the armature by an amount sufficient to set up a local field under the interpole which will establish an e.m.f. in the short circuited coils opposite to that set up by the commutated coils themselves and practically equal to it. The excess ampere turns required on the commutated poles is therefore for magnetizing purposes only and the amount of extra ampere turns will depend upon the value of the commutating field required, depth of air-gap under the commutating pole, etc. The commutating field required is obviously a function of the self induction of the commutated coil and evidently the lower the self induction the less commutating field will be required. It is evident therefore that the commutating field under the commutating pole bears no fixed relation to the armature ampere turns or to the main field ampere turns, but is, to a certain extent, dependent upon the proportions of each individual machine.

It is evident that the magnetomotive force of a given armature varies directly with the current delivered, regardless of the voltage. Therefore, that part of the interpole magnetomotive force which neutralizes that of the armature should also vary directly in proportion to the armature current. Also, the self induction of the commutated coils will vary in proportion to the armature current carried, and therefore the magnetic field under the interpole for neutralizing this self induction should also vary in proportion to the armature current. It is therefore obvious that if the main armature current be put through the interpole winding, the magnetomotive force of this winding will vary in the proper proportion to give correct commutating conditions as the armature current varies, regardless of the voltage of the machine. This is on the assumption that the entire magnetomotive force of the interpole winding is effective at the air gap and armature, which implies an absence of saturation in the interpole magnetic circuit. In the usual construction, the interpole winding always carries the main armature current as indicated above.

One consequence of the use of the interpole is that somewhat less regard need be paid to keeping the self induction of the commutating coil at its lowest value. In consequence, there is somewhat more freedom in proportioning the armature winding, slots, etc., than in a non-interpole machine, and advantage can be taken of this in bettering the proportions for other characteristics. The conditions of design are therefore not as rigid in the interpole as in the non-interpole type.

The above description of the interpole generator has been gone into rather fully, as many of the points mentioned will be referred to again in connection with interpoles on synchronous converters.

The synchronous converter differs from the direct current generator in one very important particular, namely, it may be considered as motor and generator combined. It receives current from a supply system the same as a motor and it delivers current to another system like a direct-current generator. The magnetomotive force of the armature winding as a motor acts in one direction, while the magnetomotive force of the armature winding as a generator acts in the opposite direction. As the input is practically equal to the output, it is evident that these two armature magnetomotive forces should practically neutralize each other, on the assumption that the armature magnetomotive force, due to the polyphase current supplied has practically the same distribution as that of the corresponding direct-current winding. Assuming that the two practically balance each other, then it is evident that one of the principal sources of commutation difficulty in direct current generators is absent in the converter and therefore the limits in commutation should be much higher than those of direct-current machines.

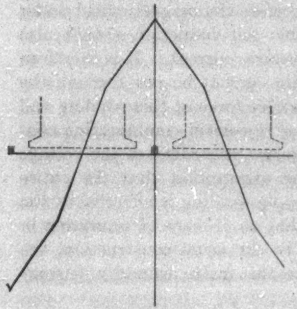


Fig. 2

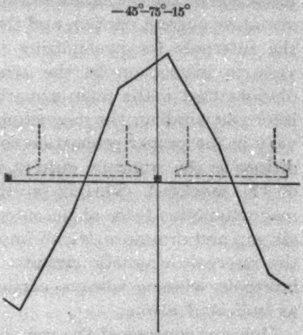


Fig. 3

The following diagram show the distribution of the alternating-current and direct-current magnetomotive forces on a six-phase rotary converter. The magnetomotive force distribution for the alternating-current input is plotted for several different positions of the armature. Three different positions are shown with the armatures displaced successively 15 electrical degrees. The general forms of these distributions repeat themselves for further similar displacements.

These distributions are illustrated in Figs. 2, 3 and 4. It is evident from these three figures that the peak value of the m netomotive force the armature varies as the armature is rotated, as indicated by the heights of the center line in the three figures.

In Fig. 5, the magnetomotive force distribution of Fig. 2 and the corresponding direct-current distribution of Fig. 1 are both shown, but in opposition to each other. In this figure both are shown in proper proportion to each other, taking into account the alternating current amperes and the direct-current amperes output. The resultant of these two distributions is also indicated in these figures.

In Fig. 6 the distributions correspond to Figs. 3 and 1 combined and the resultant is also shown.

Fig. 7 combines Figs. 4 and 1.

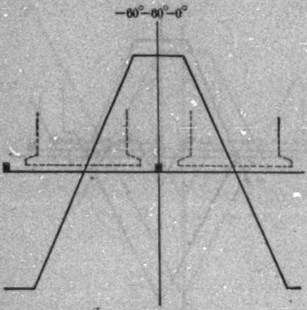


FIG. 4

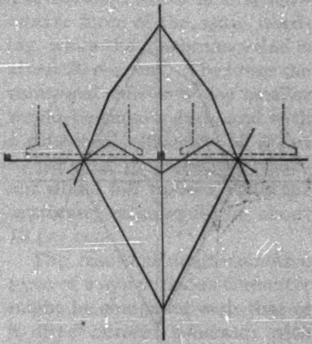


FIG. 5

It is the resultant magnetomotive force in these three figures which is important, as this is the effective magnetomotive force which tends to produce a flux or field over the commutated coil. It is evident from these figures, which are drawn to scale, that this resultant varies in height as the armature is rotated, but the maximum is only a relatively small per cent of the direct-current magnetomotive force. Therefore, it is obvious that one of the principal sources of difficulty in the commutation of the direct-current generator is practically absent in the converter, and it is also evident from this that the commutating conditions in the latter should be materially easier than in the former. This has proved to be true by wide experience in the construction and operation of converters.

In the above figures the magnetomotive forces have been plotted to scale on the following basis:

The six-phase converter winding is connected to three transformers with the so-called diametral arrangement; each of the three secondaries is connected across the diameter, or across 180 deg. points on the winding, the three diameters being displaced 60 deg. with respect to each other. Assuming the direct current in the winding as A, then the maximum value of the alternating current in any one phase of the alternating-current end will be equal to $\frac{2}{3} A$, or 0.667 A, assuming 100 per cent efficiency. However, as the alternating-current input must be somewhat greater than the direct-current output, due to certain losses in the machine, it is evident that the maximum alternating current in any one phase must be somewhat greater than 0.667 A. The field copper losses may be considered as part of the output of the rotary. The armature copper losess may be considered as due to an ohmic drop between the counter e.m.f. of the armature and the transformer e.m.f., and simply a higher transformer e.m.f. must be supplied to overcome this drop and therefore it does not effect the true current input of the rotary. However, the losses due to rotation, such as iron loss and the friction and windage are excess losses which represent extra current which must be supplied to the alternating-current end of the rotary. These rotational losses will usually be relatively small in a 25-cycle converter, being possibly 4 per cent or 5 per

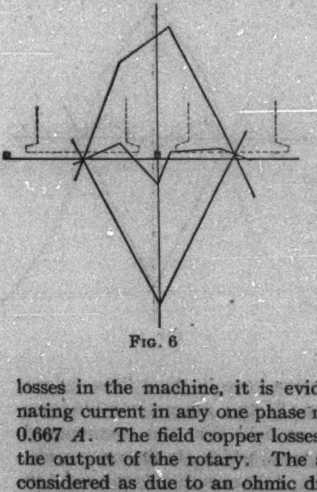


Fig. 6

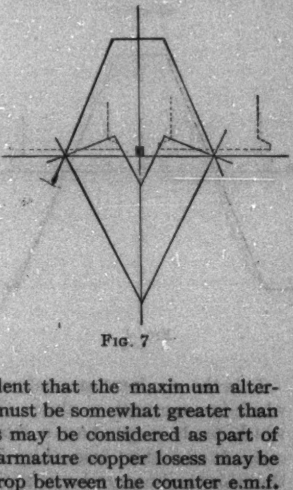


Fig. 7

cent in a small machine and 1½ per cent to 3 per cent in a large machine. In the 60-cycle converters, where the iron losses are relatively higher and the speeds are somewhat higher, giving greater friction and windage, the rotation losses may be considerably greater than on 25-cycle machines. Assuming these rotation losses will be 3 per cent, then the maximum alternating current per phase $= \frac{0.667\,A}{0.97} = 0.687\,A$. The foregoing Figs. 5, 6 and 7 are worked out on this assumption of 97 per cent rotational efficiency and on this basis of minimum value of the resultant magnetomotive force of the armature at the direct-current brush is about 7 per cent of the direct-current magnetomotive force of the same wording, while the maximum value is about 20 per cent. The lower the rotational efficiency the smaller would be these values, and with a rotational efficiency of about 89 per cent, the minimum resultant would fall to zero, while the maximum value would be about 13 per cent.

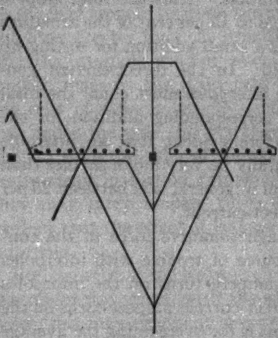


FIG. 8

The resultant magnetomotive force of a synchronous converter might be compared with that of a direct-current generator with compensating windings in the pole faces. It is generally known that such direct-current generators have much better commutating conditions than ordinary uncompensated machines. If such compensating winding on the field of a direct-current machine covered symmetrically the whole armature surface, then the armature reaction could be completely annulled, which is not the case in the converter. But with compensating windings located only in the pole faces, then the armature magnetomotive force midway between the poles could not be completely annulled, unless over-compensation is used, and the resultant would be as shown in Fig. 8, which is not quite as good as the average resultant in the converter. The commutating conditions in the converter can therefore be considered as at least as good as in a direct-current generator with a compensating winding of normal value located in the pole faces only.

In the application of interpoles to the synchronous converter the same principles should hold as in a direct-current generator, namely, the interpole magnetomotive force should be sufficient to neutralize that of the armature winding and, in addition, should set up a small magnetic flux sufficient to overcome the self induction of the commutated coil. As the magnetomotive force the armature varies between 7 per cent and 20 per cent shown in the above figures, it is evident that perfect compensation of this cannot be obtained and that therefore only some average value can be applied. Assuming that 15 per cent will be required on the average to compensate for this, then in addition the interpole winding must carry ampere turns sufficient to set up the small magnetic field for commutation. Thus the total ampere turns on the interpole will be equal to 15 per cent of the armature direct-current ampere turns plus a small addition for setting up the useful or commutating field. In the direct-current generator, the ampere turns on the interpoles must equal the total armature ampere turns plus a corresponding addition for the commutating field. It is therefore evident that an interpole winding on a converter will naturally be very much smaller than on a direct-current generator, and in general it is between 25 per cent and 40 per cent of the direct-current.

In the pulsating resultant magnetomotive force in the converter there lies one possible source of trouble with interpoles Assume, for example, the total ampere turns on the interpoles are equal to 30 per cent of the direct-current ampere turns on the rotary and that 15 per cent of this is for overcoming the average value of the resultant magnetomotive force, then an average of 15 per cent will be available for setting up a commutating field; but, according to the above diagrams, the resultant magnetomotive force of the armature varies from 7 per cent to 20 per cent. With a total interpole winding representing 30 per cent, then the effective or magnetizing part will vary from 30–7 to 30–20; that is, from 23 per cent to 10 per cent. The effective magnetomotive force therefore tends to vary over quite a wide range so that the commutating field would also tend to vary up or down over a very considerable range, which is an undesirable thing for commutation. However, as this pulsation is at a fairly high frequency it tends to damp itself out by setting up eddy currents in the structure of the magnetic circuit. If a good conducting damper or closed circuit were placed around the interpole, it is probable that this pulsation would be almost completely eliminated, but such a damper possesses certain disadvantages, as will be shown later.

In practice this pulsation of the armature reaction under the interpoles is apparently not noticeably harmful in most cases, as evidenced by the fact that well-proportioned interpole converters in commercial service show no undue trouble at the commutator or brushes.

Due to the relatively small number of ampere turns required on the interpole of a converter compared with those required on a direct-current generator, the design of the interpoles in the two cases presents quite different problems. In the direct-current generator the interpoles carry ampere turns, which in all cases are greater than the armature ampere turns, as explained before. As the field ampere turns on the main poles are, not infrequently, but little greater than the armature ampere turns, it is evident that the interpole winding may, in some cases, carry as many ampere turns as the main field windings. While but a small per cent of these interpole windings is effective in producing flux under the pole tip, yet they are all effective in producing leakage from the sides of the poles. As the interpoles are generally small in section compared with the main poles, and as they may carry ampere turns equal to the main poles, it is evident that the effect of leakage may be relatively great on the interpole.

For instance, if the leakage on the main poles is 15 per cent of the useful flux, then, with the same total leakage on the interpoles, this may represent a very high value compared with the useful flux, due to the small section of the interpole and the relatively low useful interpole flux. In consequence, it is considerable of a problem to proportion the interpoles of a direct current generator so that the leakage flux will not saturate the interpoles at some part of the circuit. If they saturate, then part of the ampere turns on the interpole are expended in such saturation and the part thus expended must be counted off from the extra or excess interpole ampere turns. If, for example, the interpole winding requires 100 per cent for overcoming the armature and there is 20 per cent extra ampere turns for setting up a useful flux, then any saturation in the interpole circuit must represent additional ampere turns on the field, as the above 120 per cent is necessary for useful flux and for neutralizing the armature. With reduced current, and consequent lower saturation, these additional interpole turns become effective in magnetizing the gap and thus the commutating flux is too strong. At greatly increased load, more ampere turns are required for saturation, and the commutating flux is altogether too weak. It is thus evident that a machine with highly saturated interpoles will not commutate equally well for all loads. Herein lies a problem in the design of interpole generators, as it is difficult to maintain a relatively low saturation in the interpoles due to their small section and high ampere turns which cause leakage. It is well known that in the main poles of the generator, a leakage flux which is higher than the useful flux is objectionable, from the designer's standpoint; and yet in the use of interpoles this is a normal condition rather than an exception.

In the synchronous converter the conditions are somewhat different due to the fact that the interpole ampere turns are usually only 25 per cent to 40 per cent as great as on a corresponding direct-current generator. The leakage at the sides of the poles becomes relatively much less, while the useful induction remains about the same as on the direct-current generator. In consequence, saturation of the poles is not so difficult to avoid. In some cases, due to the smaller ampere turns on the interpole winding, the interpole coils can be located nearer the pole tip and thus the leakage can be further reduced. However, the placing of the interpole coil over the whole length of the pole is not as objectionable in the converter interpole as it is on the direct-current generator as the ampere turns are less. It is those ampere turns which are located close to the yoke, or furthest away from the pole tip, which produce the highest leakage, while those close to the pole tip usually produce much less leakage, but in interpole generators with their high number of ampere turns on the interpoles it is often difficult to find space for the interpole winding, even if distributed over the whole pole length. In some cases, a direct-current machine may be larger than would otherwise be required, simply to obtain space for the interpole winding. This is not true to the same extent in the application of interpoles to converters.

In the above the leakage is referred to as a function of the interpole winding as if the main winding had little or nothing to do with it. The reason for this may be given as follows:

Fig. 9 represents two main poles and an interpole of a direct-current generator or converter, with their windings in place. The direction of current or polarity of each side of each coil is also indicated by + or −. It is evident that between the interpole and one main pole, the interpole winding and the main field winding are of the same polarity, while on the opposite side of the interpole, these two windings are in opposition. Let A equal the ampere turns of the interpole and B the ampere turns in the main coil. Then, $A+B$ will represent the leakage ampere turns at one side of the interpole and $A-B$ will represent the leakage ampere turns at the other side. Therefore, the leakage at the two sides of the poles is represented by $(A+B)+(A-B) = 2A$; that is, the leakage could be considered as due to the interpole winding entirely and may also be considered as due to double the interpole turns acting as one side of the interpole only. Another way of looking at this is to consider that the windings on the main pole produce leakage in the interpoles, but the leakage due to one main pole acts radially in one direction in the interpole, while that due to the other main pole is in the opposite direction.

Considering therefore the interpole leakage as being due to the interpole ampere turns only, it is evident that the synchronous converter will not be troubled with saturation of the interpoles to the same extent as a direct-current generator. With the same size of interpole it is evident that the converter should be able to carry heavier overloads than the direct-current generator before saturation of the interpoles is reached.

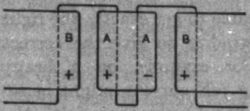


FIG. 9

It was mentioned before that a closed conducting circuit around the interpoles would be objectionable. This has been proved by experience with interpole generators. It is evident from the preceding analysis that the ampere turns on the interpole of a direct-current generator should always rise or fall in proportion to the armature ampere turns in order to give best commutation, assuming, of course, no saturation of the poles. If the interpole turns are directly in series with the armature winding, with no shunt across the interpole winding, it is evident that the interpole ampere turns must vary in direct proportion to the armature ampere turns. However, if a non-inductive shunt, for instance, were connected across the interpole winding in order to shunt part of the current, then in the event of a sudden change in load, the interpole winding being inductive due to its iron core and the shunt being non-inductive, the momentary division of current during a change in load would not be the same as under steady conditions. In other words, if the armature and interpole current were suddenly increased, then a large part of the increase would momentarily pass through the non-inductive interpole shunt until steady conditions were again attained. In consequence, the interpole ampere turns would not increase in proportion to the armature ampere turns just at the critical time when the proper commutating field should be obtained.

The same condition is approximated when a separate conducting circuit is closed around the interpole. A sudden change in the current in the interpole winding, causes a change in the flux, and secondary currents are set up in the closed circuit, which always act in such a way as to oppose any change in the flux, whereas, the flux in reality should change directly with the current. The above described non-inductive shunt across the interpole winding might be considered also as completing a closed circuit with the interpole winding, and therefore retarding secondary currents would be set up in this closed circuit with any change in the flux in the interpole.

In some cases it may be impracticable to get exactly the right number of turns on the interpole winding to give the correct interpole magnetomotive force. For example, on a heavy current machine, 1.8 turns carrying full current might be required on each interpole. If two turns were used, with the extra current shunted, the right interpole strength would be obtained. A non-inductive shunt, however, is bad, as shown above. However, if an inductive shunt is used, instead of non-inductive, and the reactance in this shunt circuit is properly adjusted, then it is possible to get the right interpole strength for normal conditions and still obtain satisfactory conditions with sudden changes in load. Also, by arranging the interpole winding so that a very considerable percentage of the current is shunted normally by an inductive shunt having a relatively high reactance compared with the interpole, it should be possible to force an excess current through the interpole winding in case of a sudden increase in load, in case a stronger commutating field were needed at this instant.

On the interpole synchronous converter a non-inductive shunt across the interpole winding should act very much as on an interpole generator and therefore non-inductive shunts are inadvisable. If any shunting is required it should be by means of an inductive shunt in those cases where the current from the converter is liable to sudden fluctuations, as in railway service. Where the service is practically steady, a non-inductive shunt should prove satisfactory for the interpoles of converters or direct-current generators.

Under extreme conditions of overload current, that is, in case of a short circuit across the terminals, it is questionable to what extent interpoles are effective. It is practicable to design interpoles on direct-current generators which will not unduly saturate up to possibly three or four times normal load. However, in case of a sudden short circuit the current delivered by the machine is liable momentarily to rise to a value anywhere from 15 to 30 times full load current. With this excessive current the interpoles of the direct-current generator must necessarily be more or less ineffective. On account of saturation, the commutating flux under the interpole cannot rise in proportion to the current. However, there should still be some commutating field present, which condition is probably considerably better than no field at all, or a strong field in the opposite direction as would be found without commutating poles. Therefore, in direct-current generators with well-proportioned interpoles, the conditions on short circuit are generally less severe than in non-interpole machines.

If the pole is highly saturated by the heavy current rush on short circuit, then it is evident that a highly inductive shunt, as described above, which would increase the interpole current in a greater proportion than the armature current, would simply mean higher saturation with little or no increase in the useful flux under the interpole.

In the synchronous converter at short circuit the conditions may be somewhat different. When the converter is short circuited it can also give extremely high currents, possibly much greater than the corresponding direct-current generator can give. Both the armature winding tied to an alternating-current supply system, and the presence of the low resistance dampers on the field magnetic circuit, tend to make the short circuit conditions more severe in the converter. The worst condition, however, would appear to be in the relation of the interpole ampere turns to the armature ampere turns on short circuit. As shown before, the normal ampere turns on the interpole winding will be only 25 per cent to 40 per cent of the direct-current ampere turns on the armature. In the case of a sudden short circuit the armature momentarily may deliver a very considerable current as a direct-current generator, and the armature reaction, or the resultant magnetomotive force, may approach that of a direct-current generator. In such case the ampere turns on the interpole will be very much smaller than the armature resultant magnetomotive force at this instant and thus there will be no commutating flux under the interpole, but, on the contrary, the armature being stronger, there will be a reverse flux which may be considerably higher than if no interpole were present, as the iron of the interpole represents an improved magnetic path for such flux. While the converter armature will probably never deliver all its energy as a direct-current generator at the instant of short circuit, yet it may be assumed that it will deliver some of its load thus, and it does not require a very large per cent to be generator action in order to neutralize, or even reverse the effect of the interpoles. In consequence, on a short circuit the converter may have a reverse field under the commutating pole, while the direct-current generator under the same condition will have a field of the proper direction but of insufficient strength which, however, is a much better condition than a field of the wrong polarity.

The inductive shunt mentioned before, which normally shunts a considerable portion of the interpole current, might be more effective in a converter than in a direct-current generator in the case of a short circuit. In a direct-current generator, the interpoles would be so highly saturated, as described before, that the increase in current in the interpole winding due to the inductive shunt would be relatively ineffective. In the converter, however, the saturation of the interpole can normally be very much lower than in the direct-current generator and it might be practicable to so proportion these interpoles that they do not saturate highly, even on short circuit. In consequence, a strong inductive shunt might force up the interpole ampere turns so that the negative field under the interpole would be much decreased, or might even be changed to a positive field and thus become useful in commutation. This would be helpful *only during the short circuit.* However, converters not infrequently flash over or "buck" when the circuit breaker is opened on a very heavy overload or a short circuit and not when the first rush of current occurs. If the flash tends to occur at the opening of the circuit, then the above mentioned inductive shunt might have just the opposite effect from what is desired, for it would tend to develop or maintain a stronger field under the interpole after the armature reaction is removed. In consequence, the heavy inductive shunt might prove harmful in such a case.

Another condition exists in a converter which does not exist in a generator. When a short circuit occurs on a direct-current generator, the armature reaction tends to distort the main field very greatly—so much so that the field of the machine is very greatly weakened. This decreases the terminal voltage and the resultant decrease in the shunt excitation will still further tend to weaken the field. In consequence, the machine tends to " kill " its magnetic field and the voltage tends to drop to a low value. Therefore, when the breaker opens on a short circuit the direct-current voltage may be falling rapidly. When the armature current is removed from the machine the voltage may rise slowly, depending upon the natural rate of building up the field. Consequently, after the breaker opens there is little or no tendency to flash, and practically all difficulties occur during the current rush, before the breaker opens. In a converter, however, the conditions are different. The armature of the converter is tied to an alternating-current supply system which tends to maintain the voltage on the converter. The machine cannot " kill " its field in the same way as the direct-current generator, for the alternating-current system tends to maintain the field by corrective currents which act in such a way as to tend to hold up the voltage. An enormous current may be drawn from the alternating-current system momentarily in case of a short circuit on the direct-current side of the converter. This heavy alternating current may cause a drop in the alternating-current lines, step-down transformers, etc., so that the supply voltage does fall very considerably and the direct-current voltage does drop materially in case of a short circuit. However, the instant the short circuit is removed by opening the breaker, then the converter at once tends to attain full voltage as the alternating-current supply system tends to bring the armature up quickly to normal voltage conditions. In consequence there may be a relatively heavy current flow in the alternating-current side of the machine, while there is no direct-current flow in the armature. Part of this alternating-current flow represents energy in bringing the machine back to a normal condition, and part is purely magnetizing or wattless current. The energy component tends to produce an armature magnetomotive force giving an active field at the point of commutation. This energy component alternating-current flow, however, cannot be corrected by interpoles, as there is no direct current flowing.

A further difference between the synchronous converter and the direct-current generator, in case of a short circuit, lies in the results of field distortion. The enormous short circut current from the converter with the armature acting partly as a direct-current generator, may very greatly shift or distort the field flux. The dampers on the field poles tend to delay this distortion. Also, after distortion has occurred they tend to maintain the distorted or shifted field so that momentarily after the circuit breaker opens the converter may be operating without direct-current load but with a very badly distorted or shifted field. This also tends to produce sparking or flashing after the direct-current breaker has opened.

Another condition which may affect the action of interpoles on converters, but which does not occur in direct-current generators, is hunting. When hunting occurs in a converter the energy current delivered to the alternating-current side of the converter pulsates, or varies up and down over a certain range, which may be either large or small. At the same time the direct-current flow is apparently varied but little. In consequence, the resultant magnetizing effects of the alternating current and direct current do not nearly neutralize each other at all times. When the alternating-current energy input is least the converter delivers part of its direct-current load as a generator, the stored energy in the rotating armature being partly given up to supplying the direct-current power. In this case the resultant magnetomotive force may be a very considerable per cent of the maximum direct-current magnetomotive force of the armature winding. Also, the magnetic field under the main poles is distorted or shifted toward one pole edge. The armature necessarily slows down during this operation, the field polarity of all the poles being shifted toward one pole edge. The position of maximum e.m.f. of the alternating-current end and also the position of maximum alternating-current flow may be shifted to a certain extent also. In consequence, the magnetomotive force due to the alternating-current flow will be shifted circumferentially a certain amount, while the direct-current magnetomotive force cannot be shifted, being fixed in position by the brushes. In consequence, the alternating-current magnetomotive force may not be in direct opposition to the direct-current at this instant, and the resultant magnetomotive force may be much higher than at normal condition. A moment later the swing may be in the opposite direction; that is, the alternating armature current may be greater than direct current and the energy being received from the alternating-current system is considerably greater than is given out by the direct current. Again, the two magnetomotive-forces will not nearly neutralize each other and there also will be field distortion, but in the opposite direction, and again, the two magnetomotive forces will not be in direct opposition to each other circumferentially. If hunting is very severe, the resultant magnetomotive force of the armature due to the inequality of the input and output, and to the circumferential shifting of the magnetomotive forces with respect to each other, may vary enormously and may pass from positive to negative values periodically. It is evident that under such condition the presence of an interpole may give much worse results than if no interpole were present; for, as mentioned before, if there is a magnetomotive force in the wrong direction at the interpole, the interpole magnetic circuit apparently makes conditions worse. In consequence, an interpole synchronous converter should be especially well designed to avoid hunting.

All of the above considerations have taken into account only the energy currents delivered to the alternating-current side of the converter. Some consideration should be given to the effect of wattless currents in connection with interpoles.

As is well known, when a synchronous converter has its field strength improperly adjusted for the required alternating-current counter e.m.f., alternating currents will flow in the armature in such a way as to correct the effect of the improper field strength; that is, if the field is too weak wattless currents will flow in the armature which tend to magnetize the field of the converter. These currents will be leading in the armature, but will be lagging with respect to the line. On the other hand, if the converter field is too strong, these wattless or corrective currents will tend to weaken the field and will lag with respect to the armature, but will lead with respect to the line. These corrective currents will have a lead or lag of 90 deg. with respect to the energy currents. Their magnetomotive forces also will have a lead or lag of 90 deg. from the magnetomotive force of the energy component of alternating-current input. As this latter practically coincides with the direct-current magnetomotive force, which is midway between the main poles, the corrective armature currents will have a maximum magnetomotive force practically under the middle of the main poles and therefore become purely magnetizing or demagnetizing due to such position. Also, being at right angles to the energy component, the magnetomotive forces of the corrective currents will have zero value where the energy component has maximum, and therefore should have no direct effect upon the resultant magnetomotive force midway between the main poles, or under the interpoles if such are used. It might be assumed therefore that the usual wattless or corrective currents, which the converter may carry on account of improper field strength, will have no direct harmful effect on the commutation. However, there are apparently some indirect effects due to this corrective current, for when a converter is operated at a bad power-factor, either leading or lagging, there is generally more trouble at the commutator and brushes than when a high power-factor is maintained.

Kw.	Volts	Poles	Rev. per min.	Cycles	Amperes per brush arm
3000	600	16	187	25	625
2000	250	18	167	25	889
1000	250	10	300	25	800
800	250	8	375	25	800
1000	250	14	514	60	570
500	250	10	720	60	400
1000	600	12	600	60	278
500	600	8	900	60	208
300	600	6	1200	60	167

It has been shown that the maximum possible benefit to be derived from interpoles in neutralizing armature reaction is much less in synchronous converters than in direct-current generators. In direct-current generators and motors interpoles have also been of great advantage, due to variable speed and variable voltage requirements. In synchronous converters, however, the requirement of variable speed is obviously absent and that of variable voltage very limited. The converter has constant voltage characteristics and variable voltage can only be obtained through the agency of such relatively expensive devices as induction regulators, synchronous boosters or split-pole constructions. The advantages of interpoles in synchronous converters are then to be looked for only in the direction of increased outputs and higher speeds.

It will be instructive, before considering the possibility of advance in this direction to take a brief survey of what has been accomplished without interpoles. The data of some machines of large output and high speed which have been built and placed in operation in the United States are given in the accompanying table.

The 3000-kw. converters mentioned above are the largest converters so far built. Eleven of these units have been installed or are being built for two of the traction companies of New York City. It is of interest to note that a number of these units are replacing 1500-kw. 250-rev. per min. units installed about ten years ago in the same substations, thereby doubling the capacity of the stations without increasing the real estate investment. The speed of these 3000-kw. units is the same as that of the 2000-kw. which, when designed four and a half years ago, represented the extreme in output and speed.

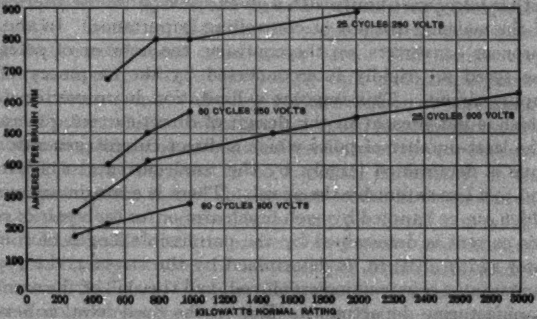


FIG. 10

The same ratings given in the table are plotted in the curve, Fig. 10, to which has been added other ratings which have been proposed and which can obviously be built in view of their relation to ratings which have been built. Fig. 10 represents concisely the situation to-day as far as the writers are familiar with it. The curves bring out very nicely the relation between permissible amperes per brush arm and frequency and voltage. It will be noted that the permissible current is greater in the 250-volt converters than in the 600-volt converters, and greater in the 25-cycle converters than in the 60-cycle converters of the same voltage. These differences call attention to the fact, important in connection with the study of interpoles, that there are limits to speed and output other than the limit affected by interpoles—the limit of sparking.

In any commutating machine the commutating conditions are dependent, to a large extent, on the number of poles. If, in a given design the commutation design constants are unduly large, the conditions can be improved by increasing the number of poles, since this, with the " parallel " windings invariably used in larger machines, increases the number of circuits in parallel and decreases the current to be commutated in a single circuit. In a direct-current generator the number of poles can be varied with in fairly wide limits with a given speed, since the alternations of the machine are not of controlling importance. In the synchronous converters, on the contrary, the number of poles and the speed are rigidly interconnected by the frequency of the supply circuit. This imposes a limitation in converter design which is not present in the design of direct-current generators. The least number of poles which a direct-current generator can have is determined largely by the total current to be handled and to a less extent by the speed. There is a maximum current which can be handled by each brush arm or for each pair of poles; this current is determined by the permissible length of commutator which, in turn, is determined by the stresses, the type of commutator construction employed, and the skill of the available manufacturing department. Due to the fixed relation between poles and speed in rotary converters, there is a fixed relation between the frequency and the commutator peripheral speed. The peripheral speed in feet per minute is equal to the alternations per minute of the supply circuit times the distance in feet between adjacent neutral points on the commutator. With the same distance between neutral points, the peripheral speed of commutators in 60-cycle converters is necessarily 2.4 times the peripheral speed of 25-cycle commutators. This does not mean that 25- and 60-cycle converters are actually built with this difference in peripheral speed, but that 60-cycle converters are pushed as high in peripheral speed as possible while 25-cycle converters are designed with a somewhat lower peripheral speed and with a proportionately greater distance between neutral points which, in turn, determine to a marked degree the sensitiveness of the machine in operation.

Another matter which has a bearing on the speed of converters is the fact that in any machine, whether an alternating-current generator, direct-current generator, or synchronous converter, there is a limit in the number of poles below which little or no reduction in cost results in spite of the increased speed. This is best shown by the relative costs of two-pole and four-pole alternating-current turbo-generators, but is also true of other machines although to a less degree where the number of poles is greater.

With these facts in mind, the difference in the high and low voltage and high and low frequency converters can be considered.

25 Cycles, 250 Volts. Due to the low frequency, low commutator peripheral speeds are possible without exceeding very conservative limits in distance between neutral points and voltage between adjacent commutator bars. This permits very long commutators, without exceeding safe mechanical limits. The large currents due to the low voltage require at best a large number of poles, which results in a low speed in revolutions, and which also simplifies the mechanical problem of the commutator design. The large currents to be handled, particularly in the larger outputs, make it desirable to push to the limit the current per brush arm. The permissible current per brush arm is high due to the favorable conditions mentioned above and the result is seen in the high values of amperes per brush arm used in converters of this class. It is evident that for converters of low voltage and low frequency the limit to further increase in speed —with consequent decrease in poles—is *length of commutator* rather than sparking.

25 Cycles, 600 Volts. As in the 250-volt converters, low frequency permits low commutator peripheral speed which, in turn, permits relatively long commutators. The smaller currents to be handled, however, permit fewer poles which results in higher speeds than in the corresponding 250-volt converters which necessitates somewhat shorter commutators. The result is that, due to the higher speeds, the limit in amperes per brush arm is lower than in the 250-volt converters. By comparing the curves for 25-cycle 600-volts, and 60-cycle 250 volts in Fig. 10 it is evident that somewhat higher values of amperes per brush arm could be used for the former, since for the same kilowatts and speed the amperes per brush arm are equal. Either the highest available speed has not been employed in existing designs, or higher speeds could be used if interpoles were added. With these converters the limits to further increase in speed is not the length of the commutator.

60 Cycles, 250 Volts. The maximum possible speed at the commutator is used in order to increase the space between neutral points, and the number of poles are chosen as small as possible without exceeding questionable operative speeds. This imposes very severe mechanical conditions in the commutator design. Going as far in this direction as is represented by the ratings mentioned above, the number of poles is still larger than would be selected in a direct-current generator of the same rating. The amperes per brush arm are smaller than in the 25-cycle converters of the same voltage due to the larger number of poles imposed by the frequency requirement.

We question, however, whether higher speeds and greater amperes per brush arm are possible without radically changing the present type of commutator construction. Here, then, as in the low-frequency, low-voltage converters, the barrier to higher speeds is found in the commutator mechanical design rather than in the electrical design.

60 Cycles, 600 Volts. As in the 250-volt, 60-cycle converters, the number of poles is made as small as possible, keeping within permissible speeds, but, with the small currents handled in 600-volt converters and the larger number of poles necessitated by the high frequency, the amperes per brush arm as shown by Fig. 10 are very low.

The limit to higher speed is obviously not amperes per brush arm. Interpoles would probably permit higher speeds due to more favorable sparking conditions, but higher speeds than those now used would certainly require changes in present commutator designs.

The higher speeds now used by the large American manufacturers of synchronous converters were introduced within a very recent date for units above 300 kw. With the relatively low commutator peripheral speeds previously used, the distance between brush arms was very small. This restricted the design to a comparatively small number of commutator bars between neutral points with a high voltage between bars, particularly in 600-volt converters. The use of a large number of poles resulted in very narrow neutral spaces between poles so that, with the combined effects of narrow neutral and high "volts per bar," 600-volt, 60-cycle converters had a bad reputation for sensitiveness to wrong brush position and to " bucking ", when compared with the substantial characteristics of low frequency converters. The later apparently radical increase in speeds has placed 60-cycle converters in the same class with the majority of 25-cycle machines now on the market in those features of design tending toward stability in operation. If this increase in speed which has been successfully accomplished without interpoles, had proven unsuccessful, due to commutation difficulties, then interpoles would without any question be justified for 60-cycle converters.

To summarize the above discussion of the various limits to increased speed: It would appear that 25-cycle, 600-volt converters offer the most promising field for the application of interpoles; that 60-cycle, 600-volt converters follow next and that 60-cycle and 25-cycle 250-volt converters show the least possibilities of improvement from the standpoint of design.

If the use of interpoles permits higher speeds and outputs than those possible without interpoles from the standpoint of commutation it will be necessary to raise our present limits imposed by the construction of commutators except possibly in 25-cycle railway converters, if advantage is to be taken of the higher speeds. These limits may be raised materially only by a change in the type of commutator construction used. In all of the converters referred to the usual *V*-ring commutator is employed. The shrink-ring construction developed for direct current turbo-generators might be used, especially for lower voltages, and the limits in peripheral speed and length of commutator be considerably extended. It may be found, however, that the use of this type would necessitate commutators of small diameter compared with those now used in synchronous converters, in order to obtain a construction of sufficient rigidity. This would in turn necessitate the use of the number of poles and speeds approaching those used in direct-current turbo-generators in order to obtain the necessary output. Such extreme proportions would apparently result in more expensive machines than those of the proportions now used without interpoles. A serious objection to the use of shrink-ring commutators is the difficulty of making repairs on them after installation. This, in general, limits the use of shrink-ring commutators to machines in which other constructions simply cannot be employed. Commutator dimensions and speeds comparable with turbo-generator practice would only be possible with 60-cycle apparatus. As a matter of fact it is not a long step from our present 60-cycle converter speeds to those usual in direct-current turbo-generators in this country. In the 300-kw., 600-volt, 60-cycle converter referred to, any further increase in speed would necessarily be from the present six poles to a four-pole converter operating at 1800 rev. per min. This is the same as the speed selected for a number of direct-current turbo-generators of 300-kw. capacity. Similarly, the 500-kw., eight-pole, 900-rev. per min. converter, if changed, would be a six-pole 1200-rev. per min. converter which is not very different from 1500 rev. per min. selected by several manufacturers for the direct-current turbo-generator of 500-kw. capacity.

The question of satisfactory commutator design for high speeds is a question that concerns the man who has to construct the commutator and the man who has to operate it, equally with the man who designs it. A large high-speed commutator is, whatever the design, a wonderful contrivance requiring constructive ability of the highest order and, when completed and put in operation, requiring careful attention on the part of the operator. Defects unnoticed at low speeds become disastrous at high speeds. The type of construction and the limits in size and speed are not to be changed without very careful consideration.

Granting that increased speeds are feasible through the use of interpoles, and that it is possible to build satisfactory commutators at the increased speeds and increased current outputs, the question still remains whether such a change results in a sufficient reduction in cost or improvement in performance to warrant the change. Considering 25-cycle, 600-volt converters, it is without question possible to build a 300-rev. per min. 1500-kw. converter without interpoles of a design in line with conservative practice. There is ample basis for the belief that still without interpoles, the speed could be increased to 375 rev. per min. without sacrificing good commutating limits, and that, with interpoles, and, assuming that a satisfactory commutator could be designed and built, the speed could be further increased to 500 rev. per min. But, comparing the material required in the eight-pole 375-rev. per min. converter and in the six-pole 500-rev. per min. converter, it will probably be found that the cost of the six-pole machine of such large capacity is as great as or greater than the eight-pole. It is also questionable whether the 750-kw. size which is now built with six poles for 500 rev. per min. could be changed to four poles and 750 rev. per min. with a decrease in cost sufficient to warrant the change.

As an illustration of what high speeds and long commutators will lead to, Fig. 11 is shown. This is a 25-cycle, eight-pole, 375-rev. per min. 800-kw. 250-volt, 3200-ampere synchronous converter. This machine carries a synchronous booster between the collector rings and the rear end of the armature, but this adds but little to the dimensions of the machine. The great length of the machine, compared with its diameter, should be noted. The use of interpoles would probably not allow any material change in the dimensions of this machine.

Considering 60-cycle converters, both 600- and 250-volt, any increase in speed would result in machines comparable with direct-current turbo-generators in type of construction and in cost. To state the matter conservatively, it is extremely doubtful whether any material increase in speeds above those now known to be possible without interpoles can be made with enough saving in cost to compensate for the expense of adding interpole windings, if such are required.

FIG. 11

The actual construction of converters with interpoles would be attended by some minor disadvantages. The field structure would be considerably complicated by the additional field winding, particularly in the case of converters for three-wire service in which both the series and interpole field windings would have to be connected in both the positive and negative circuits. In all cases the addition of the interpole would considerably crowd the field structure and increase the temperature rises in the converter unless it were designed with greater diameter to provide sufficient space for the interpoles without crowding. The efficiency of an interpole machine would in general be slightly lower than that of the corresponding machine without interpoles, due to the addition of the interpole losses. In the event of the use of higher speeds, the efficiencies will be considerably lowered by the increased friction loss due to the bearings, brushes and windage, unless the reduction in iron and copper losses is sufficient to compensate for the increased friction.

The advantages and disadvantages chargeable to interpoles may be summarized as follows:

1. Assuming that considerably higher speeds could be used:

Advantages.

a. Possible reduction in cost.
b. Less attention required in operation.
c. Longer life of commutator and brushes.

The advantages *b* and *c* may be more than counterbalanced under the present assumption, by the greater difficulty of maintaining any commutator in proper condition with the higher speed assumed.

Disadvantages.

a. Possibility of increased trouble from bucking on sudden changes in load or short circuits.
b. Possible reduction in efficiencies, particularly in light load.
c. Higher operating temperatures unless the same temperatures as now obtained in non-interpole machines are maintained by partly sacrificing the advantage of lower cost.

2. On the assumption that no higher speeds will be used with interpoles than have been found to be practicable without interpoles, but that the interpoles will be added simply as a refinement to machines that would operate satisfactorily without them.

Advantages.

a. Less attention required during operation.
b. Longer life of commutator and brushes.

Disadvantages.

a. Possibility of increased trouble from bucking on sudden changes in load or short circuits.
b. Slightly lower efficiencies.
c. Higher operating temperatures.
d. Greater cost due to the addition of interpoles.

This is true of course only with the stated assumption that the converter is designed to operate satisfactorily without interpoles. It would probably be possible to design a converter with interpoles without exceeding the cost of the non-interpole machine as has been done in other types of apparatus, but this would be done by making a machine which is unsatisfactory without interpoles and then improving the commutating conditions by interpoles. Such result, however, would hardly represent an improvement over present practice.

In conclusion, the authors have attempted to state the case for and against interpoles in all fairness. From the standpoint of design it seems difficult to make a sufficiently strong case for the interpole in synchronous converters to warrant the additional complication in construction. At best the addition of interpoles, properly applied, represents a refinement over present designs, and the fundamental question is whether such refinement is justified commercially. This question, however, must be decided, as all engineering problems are finally decided, not by the judgment of one man or any group of men, but by the results of experience in extended operation.

DISCUSSION ON "INTERPOLES IN SYNCHRONOUS CONVERTERS," NEW YORK, NOVEMBER 11, 1910.

Gano Dunn: This subject comes under the head of commutation, which Lord Kelvin used to lament was neglected in former years by the drawing away of the best minds in electrical engineering from direct current problems to the more interesting and complicated alternating current problems; although Lord Kelvin also said the problems of commutation were really more complicated than the problems in alternating current for which they were neglected.

To-night's paper, with the discussion expected, shows that the best minds are coming back again to the old subject of commutation, with a resolve to solve some of the difficulties that have been waiting so many years asleep, for the kinds of men that are now giving them attention.

There are two kinds of commutation; magnetic commutation, and what may be called resistance commutation, although the resistance referred to is that of the contact of the brush with the commutator and produces an effect similar to what would be produced by a counter electromotive force at this contact.

Resistance commutation depends upon this so-called counter electromotive force of contact under the heel of the brush for the reversal of the coil.

Magnetic commutation depends for the reversal of the coil, upon the direct electromotive force generated in it by either the magnetic fringe at the pole tip or by an auxiliary pole.

Under the action of the auxiliary or commutating pole the current in each coil of the arch of coils approaching the commutating region, is reversed at the same time that the coil is transferred from the approaching to the receding arch.

All commutating or interpole subjects belong under the head of magnetic commutation.

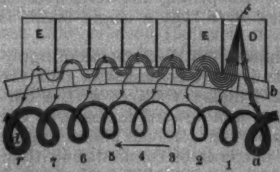
Interpoles have been known for many years, my first discussion of them being in a lecture delivered in 1893, but for many reasons, which this is not the occasion to mention, they were not taken up for constant speed machines until, when either through increased size or increased speed and after the number of turns had been decreased to one per bar, the volume of current loaded on the armature turns of dynamo electric machinery became larger than a carbon brush could, by resistance commutation, satisfactorily reverse.

A further reduction of turns per bar was impossible for the same reason that you cannot make a clock that will strike less than one, and there seemed at that time to be no known means of increasing the so-called counter electromotive force of contact of the brush. Interpoles were therefore resorted to, for the proper turning over of the heavy currents in the coil which had grown beyond the capacity of the brush to handle in the time allowed.

When taken up, interpoles were adopted very rapidly, becoming a fad and being used in many cases where they were not, as physicians say, " indicated," and I am glad to see in the paper a conservative tendency in regard to their use in rotary converters.

I wish to point out an improvement that has been made in resistance commutation, which may increase the range of applicability of that type of commutation into the field of interpoles. It is not yet satisfactorily developed commercially but may be of use as an alternative to the interpole, to those who are searching for means for improving the commutation of rotary converters.

I refer to what I have called fractional commutation, the principle involved in which was developed by Mr. F. W. Young and was mentioned at the Asheville Convention of the Institute. It applies particularly to machines whose voltage is, in a direct current sense, high. The improvement depends upon an increase in the counter electromotive force of the brush contact by putting a number of these contacts in series with the coil that is about to leave the brush.



If in the accompanying figure, *b* represents a commutator moving to the left and *D* represents the main brush connected to the line, and *E* and the brushes next to it represent brushes that are neither connected to the line nor to each other nor to the main brush *D*, but all dead and merely lying adjacent to each other in such a relation that each brush has the width of a commutator bar, then as the commutator moves to the left the last thread of current that is about to be sheared off from entering the coil *R*, it will be seen has had to travel successively from the main brush *D* against approximately one volt counter electromotive force into the commutator bar under it, then back upward out of the commutator bar against another one volt counter electromotive force into the first dead brush *E*, then down again through another counter electromotive force into the next commutator bar, then up again into the next dead brush, and so on, and in the case shown in the figure, assuming one volt counter electromotive force for each contact surface past, will have encountered thirteen volts counter electromotive force.

It is this last thread of current that makes the spark, and while the number of dead brushes used in the figure is large, merely to illustrate the principle, it is astonishing what excellent results are obtained with only two or even three dead brushes.

With three dead brushes there are seven volts counter electromotive force, which gives results comparable to the best that interpoles can do.

One dead brush alone increases the counter electromotive force at the heel of the main brush, from one volt to three volts, and roughly speaking extends to three times its former range, the powers of resistance commutation.

The reason for calling the method of commutation I have here described, fractional commutation, is that it secures the reversal of the current in the coil step by step, a little at a time as the coil passes each dead brush.

The fractional nature of the commutation can easily be seen by counting the number of threads of current running to each coil in the diagram. This illustrates quantitatively about how the current would actually change in the coil as it passed from a position on the extreme right of the figure to a position on the extreme left.

The net results are: The total time a coil is subjected to the influence of commutation is increased. In other words, the coil has warning of what is going to be expected of it in a way it does not have when there is only a single brush. And the electromotive force available for compelling the turn over of the coil is increased many times over that a single brush is capable of developing.

This system of fractional commutation does not seem applicable where currents are large and where commutator bars are wide, but with tendencies toward higher voltages with a corresponding diminution of current, and toward increase in the number and fineness of commutator bars, we can afford to give more commutator space to the purposes of commutation than formerly. I believe there is a principle in this method, that with some further development can be made extremely valuable and is well worthy of study. I have spent considerable time on it and conducted a great many experiments, with results, that while not yet commercial, indicate that the principle is sound. In certain cases fractional commutation of this kind would have many advantages over the magnetic commutation of interpoles.

H. F. T. Erben: The paper which has just been read is a clear exposition of the subject of commutation and general operation of synchronous converters with and without commutating poles.

While I agree with the general conclusions arrived at in the paper I do not think the authors dwell at sufficient length on one of the broadest fields of usefulness for converters with commutating poles, namely, for those operating on interurban service and for high voltage converters wound for 1000 to 1500 volts. The machines I refer to are those in which the general characteristics of design are determined solely by commutating conditions at heavy overloads and not by any consideration of heating. It seems to me that the conclusions which the authors of the paper have drawn regarding the advantages and disadvantages of commutating pole converters are pertinent principally to units used in connection with large central station systems in which the prime consideration of design is not commutation but heating, efficiency, and low maintenance. Synchronous converters installed in our large cities in connection with railway work have as a rule a very constant duty and are not subject to heavy overloads, the maximum as a rule not being greater than 50 per cent overload and in consequence I agree that for such service interpoles are unnecessary. On the other hand, converters used in connection with interurban service have a very low load factor but are subject to very heavy overloads, possibly two or three times normal and for such service I believe that commutating poles are a necessity.

During the past few years a number of 1200- and 1300-volt interurban systems have been put into successful operation and as a rule the generating apparatus has consisted of either two, 600-volt generators or converters in series. Single generator units wound for 1200 volts with commutating poles have been in successful operation for the past two or three years and at the present time some 1600-volt commutating pole generators are being built. I venture to predict that within two years we shall see 1200- or even 1500-volt single unit synchronous converters in operation on long interurban lines. I do not believe that any designer would be willing to build a 1200- or 1500-volt converter without providing commutating poles, as he is faced with the problem of producing a machine which is capable of withstanding momentarily overloads of two and three times normal without severe sparking or flashing, which is a condition very difficult of attainment on machines of the non-commutating pole type.

The experiments which we have carried on in connection with 1200-volt, 25-cycle converters show that if the commutating poles are properly proportioned, little is to be feared in the way of flashing within what one might consider the limits of daily service. We have repeatedly subjected a 750-kw. 1200-volt converter to four times normal load without any signs of flashing when the load was suddenly removed. In order to determine the damage, if any, resulting from flashing caused by a dead short circuit, we have repeatedly subjected the same converter to short circuits through a few feet of cable. Although the flash produced was of large volume we found that neither the commutator leads, brush-holders nor brushes were damaged to any appreciable extent. In fact, after the machine had been short-circuited six times it was immediately brought up to normal load and overloads without appreciable sparking.

I believe that the authors have laid too much stress on the effect of the various magnetomotive forces in connection with flashing. A long series of experiments made to obtain data on the flashing of various types of machines at time of short circuit has shown that there is little to choose, as far as flashing goes, between direct-current machines of the non-commutating pole and commutating pole type. Of course, commutating poles or compensating windings will help to a certain extent but if the short circuit causes the armature current to rise to say ten or fifteen times normal, the machine will surely flash over.

The authors call attention to the fact that when subjected to a dead short circuit a synchronous converter will behave differently from a generator, due to the fact that the commutating pole of the generator will become highly saturated, whereas the commutating pole of the converter will not have reached saturation. If one considers that at the time of a short circuit on either a rotary or generator the current may rise to fifteen to twenty times normal, such an increase in magnetomotive force will be sufficient to over-saturate the commutating pole, although in the case of the converter the value of the magnetomotive force will be less than on the generator.

The authors have stated that an inductive shunt used in connection with a generator or rotary may be of considerable value in helping commutation at the time a heavy load is thrown on but it might be a detriment when the load is thrown suddenly off. I hardly agree with their conclusions, as it has been shown in actual practice that a properly proportioned inductive shunt will cause the flux in the commutating pole to instantly drop to zero, in fact the inductive shunt may be so proportioned as to actually reverse the direction of flux in the commutating pole at the instant the breaker is opened. If the flux in the commutating field can be instantly brought to zero or reversed as has been shown possible by oscillograph records, there will be little or no chance of the machine flashing over except of course, in case of what is practically a dead short circuit.

C. P. Steinmetz: I agree with the conclusions in this paper in their general nature. They are that the commutating pole offers relatively little if any advantage in improving the design of the converter as at present built. There may be a slight advantage in 600-volt 25-cycle converters, which means that in 1200-volt, 25-cycle converters there would be a greater advantage and a still greater advantage in 2400-volt, 25-cycle converters; the former are with us now in operating 1200-volt railway service, and the others I believe will come at a not far distant future.

The paper is very interesting in showing that in electrical engineering investigations the conclusion which we arrive at depends very largely on the view point regarding conditions of operation and application of the apparatus. That is, they depend on the premises on which the study is based. In this paper a converter is considered with the design constants proportioned as they are today in large converters operated on steady service in our big lighting systems, at 250 volts, and on our big metropolitan railway systems, of very steady loads; and in this class of converters there is relatively little gain in the use of commutating poles. But let us take another view point, starting from different premises as regards the requirements of operation and see whether some different conclusions may not be derived. The overload capacity of the synchronous converter depends on the supply system, the heating limit, and the sparking limit. The supply system can be controlled by its design. If a converter in an interurban railway system has to stand overloads of 300 or 400 per cent, it means that the feeder or the transmission line must be sufficient to give that load without a drop of voltage such as would disturb the machine. If the load is steady and uniform the heating limit is a material limit. If the load is widely fluctuating with relatively low load factor, as in interurban railway service, where the load rapidly fluctuates between almost no-load and a load of short duration amounting to several hundred per cent overload, then the heating limit is eliminated, because the greatest length of time at which the converter may be overloaded is only the time that the train passes over that section, a few minutes, and during that interval the heating limit, even at three or four hundred per cent load, is not reached. That means that the only limit of overload capacity is the commutation limit. In the converter the armature reactions neutralize. Thus the sparking limit is determined by the self induction of commutation and this is controlled by the commutating poles.

It will be seen in that class of service, which is quite common and constantly increasing, where the load is very fluctuating, the load factor very low, and where, therefore, the only limit of overload capacity is the commutation limit, the commutating pole offers us a very material advantage in the design of the synchronous converter, by making it possible to greatly increase the overload which the machine will carry. In other words, for the same kind of service, we can build a converter whose rated load is much smaller and thus much nearer the average load. That is to say, we very greatly increase the load factor of the machine as based on its rated load, and therefore its efficiency of operation, and the efficiency of operation of the station and of the entire system.

When we come to an interurban railway system with infrequent heavy service, this feature may be and often is the difference between success and failure of the system; the nature of the load is so fluctuating, of such a low load factor, that we can get efficiency of operation only by a machine which can carry for a short time enormous overloads. Hence, as the heating limit is absent, the commutating pole gives us a very material advantage by making a smaller and a lighter machine. It is not only this advantage of better load factor, but coincident therewith is the advantage gained in the lesser liability to hunting, because the hunting of a synchronous machine is determined largely by its mechanical momentum, and if we can decrease the momentum of the machine by making it smaller it means that we will have greatly improved its stability.

As regards the danger of flashing due to unbalanced armature reaction, as illustrated in the paper, I will say that theoretically, the problem is there, but practically I do not believe it is material for the reason that I do not think that such unbalanced armature action can exist to any appreciable extent. If, as illustrated, the armature reaction should be unbalanced by a sudden heavy load thrown on the machine, without any corresponding or neutralizing alternating m.m.f., it means that the energy output will have to draw on the momentum of the converter by a decrease of speed. But we know that the converter cannot decrease in speed because it is locked synchronously. So it cannot gain any energy from the mechanical momentum except that insignificant amount corresponding to the drop in position—not in speed—from no-load position to the overload position, which, in a converter where the reaction is balanced, is extremely small. If we cannot draw on the mechanical momentum for energy, either the energy will not flow out and the machine will not take the load instantly, or it must at the same time flow in and then the reaction is balanced. The same thing happens again if you suddenly throw off the excessive overload. That means that the power input would accelerate the machine. But synchronism eliminates the chance of acceleration, so that we get only the momentum of the speed which shifts the machine from the relative position corresponding to one load to that of another load; that is, a momentum which involves a fraction of a cycle. But even this effect eliminates itself, because if the machine shifts from one position to another position by dropping back or running ahead, then it does not only drop into the new position, but it runs beyond it before it stops. That means it overreaches, and if there was an excess of the direct current it must be followed instantly by an excess of the alternating current and inversely, which reverses the former's effect.

Since the poles are solid iron, I do not see how you can get any appreciable effect in this direction, especially if the mechanical momentum of the machine is very small, due to its enormous overload capacity. So the momentum on which you can draw to give an output is very small. That possibly explains why converters designed with commutating poles even at very high voltages, 1200 or so, do not flash over under conditions of operation under an excess of overload, as it was expected theoretically that they would do.

Jens Bache-Wiig: In the paper by Messrs. Lamme and Newbury the probable effect of the interpoles in case of a sudden short circuit on the direct current side of the converter is brought out. It is reasonable to assume that the presence of the interpoles in case of a short circuit will tend, if anything, to increase the injurious effect on account of the unbalanced ratio between the armature and interpole ampere-turns, as pointed out in the paper. As is well-known, the effect of a short-circuit upon the converter often results in the voltage flashing over and, in consequence, the commutator and brush-holder parts are badly burned. The effect may be such that it is necessary to shut down the converter and clean it up before starting again. The large current flowing during the short-circuit will form an arc between the nearest points of different polarity and it will to a great extent depend upon the action of the alternating-current circuit breaker how bad the effect will be. Ordinarily, it is the alternating-current circuit or the power behind the rotary which determines the flow of short circuit current. Therefore, if this power behind the rotary could be eliminated at the moment of the short-circuit, the effect of the latter upon the rotary would be greatly reduced and would be determined only by the inherent characteristics of the rotary itself. The action of the rotary in case of a short circuit on the direct-current side would then be approximately the same as that of a direct-current generator of similar size. The injurious effect in this case would be small, as brought out in the paper.

It is customary to protect the converter on the alternating-current side by a circuit-breaker, having a maximum relay set for a certain current at which it is supposed to open the circuit and throw the converter off the line. Similarly, it is customary to have a maximum relay breaker on the direct-current side. In case now of a short-circuit on the direct-current side, a large momentary current will be drawn from the converter greatly exceeding the actual current required to open the direct-current breaker. As soon as the direct-current breaker lets go, this current which is rushing through the rotary will suddenly be brought to a stop and it is this sudden change in the flow of current which usually causes the flashing, in combination with the fact that the direct-current breaker lets go before the alternating-current breaker. This now can be overcome by arranging for an electric interlock between the direct-current and alternating-current breaker in such a manner that the alternating-current breaker lets go at the moment the direct-current breaker drops out. This can be arranged for by a tripping coil on the alternating current breaker operated by the direct-current breaker. In this manner the danger of flashing due to short circuits on the line can be greatly reduced if not wholly eliminated. This is of special importance in case of interpole converters.

As to the effect of such an arrangement from an operating point of view, there should in case of self-starting converters be no objection to it. It is true that the converter is altogether thrown off the circuit and may be thrown off oftener than would be the case if it was not arranged in this manner. However, if the attendance is present in case the breaker goes out, all he has to do is to throw it in again, and thus get it back in service at once. If he is not there, it is in most cases better to have the rotary stay out of service than it is to take any chances on flashing and its possible evil effects.

As regard the presence of the interpoles in case of hunting and their effect upon the operation of the rotary under such a condition, it may be said that while the interpoles may to an extent cause a less satisfactory operation than would be obtained without them, yet, with the present complete type of damper employed on many synchronous converters the liability of hunting in itself is practically eliminated. Barring the common causes for hunting which are excessive ohmic line drop and periodic impulses set up by the prime movers, as these can be guarded against in a well-designed power circuit, there remains as a source of hunting the possibility of short circuits on the system or the switching in and out of large units, causing heavy surges in the power circuit. However, in case effective dampers are employed, the hunting caused by these surges as quickly damped out and the effect will be of such short duration that it should not be harmful to the rotary. In case of a dead short circuit, the rotary will of course kick itself out and will have to be started over again. It seems evident, therefore, that the highest grade of dampers should be employed wherever interpoles are used on the rotary converters.

P. M. Lincoln: This term "interpole" has been somewhat loosely used. Interpoles in synchronous converters are used for more than one purpose. The kind discussed in this paper is used purely for commutation purposes. An interpole or split pole, has also been used for the purpose of varying the direct-current voltage, and I have noticed in some of the literature a confusion in the use of these two kinds of poles. In fact, in reading an abstract of an article in a foreign journal some time ago it was impossible for me to tell whether the author was discussing interpoles used for commutating purposes or interpoles used for the purpose of changing the direct-current voltage.

This paper is exceedingly clear in its presentation of the method by which the interpole works. The authors show very clearly that the inherent commutating characteristics of the rotary converter are very much better than they can possibly be in the case of the alternating-current generator. Any one can get this information for himself if he will endeavor to run a rotary converter as an alternating-current generator. Sparking at the commutator will begin at a point which will astonish the man who conducts the experiment unless he knows what to expect. One can take liberties with the commutation of a rotary converter for the reasons set forth in the paper, *viz.*, because the armature reaction due to the direct-current flowing, is practically all neutralized by the alternating-current.

It is also shown in the paper that a commutating pole on the rotary converters is necessary only in extreme conditions. It is only when the speed or the output reaches a high value that it is necessary to resort to the commutating poles in the rotary converter.

This brings out another point which might be mentioned, and that is that if conditions requiring commutating poles are approached in rotary converters it is impossible in such a condition to use the split-pole rotary converter because the latter does take considerable liberty with the commutating conditions

J. L. Burnham: The authors of this paper state that there is a limit to speed and reduction in number of poles, which cannot be exceeded with economy. For instance, for 25-cycle, 600-volt converters, it has been found that an output of about 150 kw. per pole is the maximum that can be handled economically without the use of interpoles where the usual specifications of 50 per cent overload for two hours and 100 per cent overload momentarily are to be fulfilled. This is on the assumption that commutation is to be good enough with ordinary carbon brushes for commutator and brushes to maintain good surfaces and require a small amount of attention. The output per pole may exceed this value by the use of very high grade and expensive brushes and greater maintenance, which may not be justified by the decrease in cost of the machine. With greater output per pole, the pole pitch must be increased to take care of the increase in size of conductor, slightly, but to a greater extent to decrease the reactance voltage to a value which will not cause excessive sparking. The limit in reactance voltage is really the factor which prevents the use of a less number of poles, since when we increase the pole arc to reduce the reactance factor in the slot portion, we increase the length of conductor outside of the slot portion, which adds to the reactance voltage and the gain in reduction of the total reactance voltage becomes less the longer the arc. In a 600-volt, 25-cycle machine, the reactance voltage generated in the conductor outside of the slot is about two-thirds of that generated in the conductor inside of the slot, when the output is 150 kw. per pole. If we attempt to increase the output, keeping the total reactance the same, the machine becomes very much larger than would be necessary with an economical proportioning of iron and copper. It is at this point that the introduction of commutating poles to increase the output per pole is of advantage.

Messrs. Lamme and Newbury have given a number of reasons why interpoles on synchronous converters may not work out as well as on direct-current generators or motors. In all of these cases the reason hinges on the fact that the ampere turns necessary for the interpole of a synchronous converter are much less than required for direct-current generator and very much smaller in proportion to the armature reaction ampere turns of the converter armature. This naturally leads to the suggestion that the required ampere turns of inter pole winding might be increased to advantage. Several months ago I conducted a number of tests, with various shapes of interpoles and lengths of air-gap, on 25-cycle, 1200-volt synchronous converters and found that with a narrow inter pole face and a very large gap, commutation comparable to that obtained with a compensated commutating pole generator could be secured. The load at which sparking would commence, without interpoles, was carefully determined. Interpoles were then fitted to the machine and adjusted so it would carry four times the load to cause the same sparking as without the interpoles. Four times full-load could be thrown on and off successfully but would always be accompanied by a slight spitting at the brushes. I attributed this to a shifting of the magnetic centres of the poles due to change in flux through the interpole and also to slight change in relative position of armature to poles, due to change in losses in the converter rather than to lag in change in commutating field. That is, the effect would be the same as produced by pulsation when the armature swings out of phase far enough to cause sparking, or when the machine is badly synchronized and thrown on to the power circuit slightly out of phase and spits at brushes several times.

Contrary to the statement of this paper, that a shunt to the commutating winding having greater inductance than the winding would be harmful, it was found in these tests that a shunt having about 50 per cent greater inductance than the winding of commutating pole gave the best results, particularly when the load was thrown off. The two circuits being in multiple, the higher inductance would reverse the current in the smaller, which reversed current would reduce the field flux more rapidly than would no current, as in the cases of equal inductance of field windings and shunt or with no shunt.

The effect of pulsating resultant armature reaction under the interpoles will be reduced in proportion to the increase of reluctance of the interpole magnetic circuit. Increasing the air-gap is the best means of increasing this reluctance since it introduces no effects of saturation.

As might be expected, the addition of interpoles causes more sparking at the commutator when starting from the alternating-current end than would be obtained without the interpoles, due to the decreased magnetic reluctance of the induced field at the point of commutation. This can be greatly improved by the large air gap and narrow commutating pole face previously mentioned.

Mr. Lincoln has pointed out the fact that commutating poles cannot be used with success on split pole converters. I would also like to add that this statement also applies to converters with direct-connected alternating-current boosters, but for somewhat different reasons. The synchronous booster when adding its voltage to the line is acting as a generator requiring corresponding motor action in the converter. When the booster is opposed to the alternating-current line voltage, it acts as a motor and drives the converter. This motor and generator action of the converter superimposed upon the converting action gives armature reactions the same as if the converter were acting only as a motor or generator. As the motor and generator reactions are in opposite directions, the total variation for ordinary conditions might easily equal the total excitation of the winding on the commutating pole adjusted for converter action only. For example, an average value of the commutating pole ampere turns would be about 30 per cent of the armature reaction. An ordinary voltage regulation would require 15 per cent boost or buck, or in other words, a motor and generator action of 15 per cent of the output. This would give a variation in armature reaction of 30 per cent, which is equal to the total full-load excitation of the commutating pole winding. Several arrangements for varying the commutating pole excitation with variations in the amount of buck or boost, as well as with variations in load, have been worked out, but they are at best rather complicated and undesirable.

C. W. Stone: Dr. Steinmetz has said practically all that I wanted to say, but I am going to try to express it in a little different way. There is one clause in the paper which is not quite clear, possibly I misinterpret what the authors mean. However, I think it is well to bring the point out more clearly. The authors say:

"Assuming the direct current in the winding as *A*, then the maximum value of the alternating current in any one phase of the alternating current end will be equal to $\frac{2}{3}$ *A* or 0.667."

I think that the authors should have said the current in the direct current leads instead of the winding, otherwise, the value would be double that stated in the paper.

I think the principal point in connection with the interpole and its use on synchronous converters, is the point raised by Dr. Steinmetz, and that is, the greater capacity that can be obtained for momentary overloads. If, as Mr. Burnham pointed out in his remarks, the momentary overload on a machine without injurious sparking can be increased to four times as much on the machine without interpoles, it is possible to use small machines in interurban railway substations. In other words, we could, in many cases, put in 200-kw. machines where 400-kw. machines are now used, which would mean economy.

The principal reason, I think, why this has not been done, has not been because the manufacturer did not want to do it, but because the operating engineers did not like to try the experiment.

I hope that this paper will cause the operating people to try this experiment in some place, and I think that the result will astonish them, and it may result in a total revision in the practice of synchronous converter substation design on interurban roads.

The authors of the paper state that the principal application would appear to be in that of 25-cycle, 600-volt converters. This, to my mind, is the smallest application. The broadest application would be that of high-voltage rotary converters, and high frequency rotary converters, and also, as stated above, for rotary converters when installed on loads which are greatly fluctuating.

It would seem to me that the conclusions which the authors reach relate more to the synchronous converter substations installed on city loads rather than on loads such as are usually found in interurban service.

One point which Mr. Lincoln spoke about in his discussion is, that with synchronous converters the alternating-current circuit-breaker opens and thus limits the damage in case of a short circuit. This is, of course, true. With the ordinary direct-current generator, driven by some form of alternating-current motor, the action of the circuit-breaker is not so quick, that is, the alternating-current circuit-breaker does not open as quickly, and the flash-over which is the cause of the short circuit will cause greater damage than on the rotary converter.

Mr. Lincoln speaks of the flashover as being caused by the sudden change in the current flow due to the circuit-breaker opening. I do not think this is usually the cause. My conception of the flash-over is that it is caused more by the sudden increase in current, which necessarily forms more or less gas at the point of contact of the brush and commutator. This gas is of low conducting value, and it is not only immediately beneath the brush but surrounding the brush, and on account of the low resistance of this gas a large arc is formed by the current passing through the gas, which creates more gas, and due to the fact that the commutator is revolving away from the brushes a part of this gas and the arc are carried over to the next brush holder and cause the flash-over.

To sum up, I think the principal advantages in the use of the interpole on synchronous converters is the possibility of using small machines to do the same work that larger machines are used for; the possibility of building successful high voltage machines, and the possibility of building high frequency machines of large capacity.

C. A. Adams: At the last meeting Professor Franklin prefaced his remarks by the statement that he found it difficult to divorce himself from the attitude of the teacher. I find myself in that same state of mind to-night. The first thought that came to me when reading this paper was that it would be an excellent one for purposes of instruction.

The greatest difficulty in teaching a subject of this kind is to bring about a thorough understanding of the phenomena involved. This cannot be done for the average student by a mathematical analysis of the problem in hand; but, since a mathematical analysis is much easier to prepare than a clear verbal exposition, and since some algebraic formulation is generally necessary for purposes of computation, the average author feels that he has covered the ground if he adds a few words of explanation to his mathematical solution. There results an abuse of formulae by those who do not understand their true inwardness and a general lack of appreciation of mathematical analysis on the part of others.

It is therefore a great pleasure to read such an admirably clear verbal presentation as that which appears in the paper under discussion. It is sure to be a great help to students of this subject. I congratulate the authors most heartily.

I had hoped to present a simple algebraic analysis showing the quantitative relations between the kilowatts per pole of a synchronous converter and some of its fundamental design constants, but it is not yet finished and in any case would better appear in print as a communication.

B. G. Lamme: I will take up a little time in answering some of the points brought out in this evening's discussion, but will not attempt to answer them in full. I also have a few additional points which I would like to bring out, which were not included in the paper of the evening, because it would have made it of undue length.

Reference has been made to the use of converters with very large overload capacities for interurban practice, and it was stated that for such a service interpoles would be advantageous. While not contending that interpoles would not be advantageous, I will call attention to the fact that for interurban service as now carried on, most of the converters furnished have been of 200 to 500 kw. capacity. Such machines, as now built, have a relatively small capacity per pole and therefore their commutating conditions as regards overload, etc., can be very much better than in very large capacity converters with large outputs per pole. Consequently, a modern design of a 300-kw., 600-volt converter, for instance, should allow commutation up to three or four times full load without excessive sparking, and even much higher than this without flashing. I have seen such machines loaded until the limit was found in the current-carrying capacity of the brushes and not in the sparking. However when machines of greater capacity are taken into account, with much larger outputs per pole, then with excessive overloads the advantages of interpoles will become much more pronounced.

Reference has also been made this evening to the use of interpole converters on 1200- and 1500-volt circuits and it has been intimated that interpoles bring up the possibility of making 2400-volt converters for 25 cycles, and also high-voltage, high-frequency converters, 1200 volts presumably being meant by this latter. Some reference was also made to the use of interpoles for helping the commutation of high-voltage converters which, it was intimated, suffered somewhat in comparison with 600-volt machines due to poorer proportioning of slots, etc., on account of the high-voltage winding.

I have gone into this problem of high voltage direct current generators and converters to a very considerable extent and, according to my figures, I find that the real limit in such machines is not in the commutation as much as in the mechanical conditions, such as peripheral speed of the commutator, thickness of commutator bars, etc., and also in the permissible voltage between bars. To illustrate this, let us assume a 25-cycle, 1500-volt converter. To begin with, the peripheral speed of the commutator, as mentioned in the paper, is equal to the *alternations per minute multiplied by the distance between adjacent neutral points on the commutator*. This is a general law and applies in all cases regardless of frequency, number of poles or revolutions per minute. Let us assume, on our 25-cycle machine, a commutator peripheral speed of 5,000 ft. per minute, which is pretty high. This gives a distance of 20 in. between adjacent neutral points and this is the maximum distance which can be obtained with this peripheral speed and frequency, regardless of the number of poles and revolutions per minute, or any other conditions. Assuming a thickness of a single commutator bar plus its mica as $\frac{3}{16}$ in. which every body will admit to be very thin, then the total number of bars which can be placed in this 20-in. space will be 107. With 2400 volts this gives about 22½ volts per bar as the average. This is much higher than is considered good practice in 600 volt machines, and naturally one would not expect to do better with 2400 volts than with 600 volts. In fact, for the same margin of safety, as a whole, we should have somewhat better conditions with 2400, or even 1200 volts, than is required with 600. However, with 107 commutator bars, which was given as possible, it may be practicable to operate at 15 volts per bar average, which will give, roughly, a 1600-volt machine as a possibility on 25 cycles. It should be remembered, however, that this is on the assumption of 5,000 ft. per minute speed of the commutator and $\frac{3}{16}$ in. thickness of commutator bar plus mica. Any reduction in the peripheral speed, or increase in the thickness of the bar, will at once lead to a smaller number of bars with a correspondingly higher voltage between bars. As an example of the approximate limit to the average voltage per bar, the company which I represent has in the past, furnished a large number of converters for 600 volts with 36 commutator bars per pole, giving 16⅔ volts per bar average. From long experience, this appears to be rather close to the limit and on later designs of 600 volt machines this voltage per bar has been reduced about 20 per cent.

Next, considering a high-frequency, high-voltage converter, and again, assuming 5,000 ft. commutator peripheral speed for a 60-cycle machine, then the distance between adjacent neutral points on the commutator becomes 8.4 in. With $\frac{3}{16}$ in. of bar plus mica, this gives 45 bars as the maximum number. For 1200 volts this means almost 27 volts per bar average, which I would consider as entirely too high for low-voltage machines. It should be noted that in neither of these cases has the question of interpoles been brought in, and the use of interpoles cannot in any way affect these conditions. The use of two windings and commutators in series on the same armature might be considered, but the arrangement is awkward and complicated.

As to the commutation of a high-voltage machine being inferior to a low voltage, this would not necessarily be true. On the contrary, the commutation should be better in some instances. Assume, for example, that the commutator has a certain number of commutator bars for 600 volts with one armature turn per bar. If the number of commutator bars is doubled for the 1200 volts, then the number of armature turns per commutator bar would remain the same. If the same number of poles were used at 1200 volts as at 600, then the current per conductor would be halved and the commutating conditions would be about twice as good as on the 600 volt machine. However, in practice this result will not always be obtained, for the number of poles may be reduced somewhat in the high voltage machines, except in the smaller capacities, such as 300 to 500 kw. where a small number of poles is already used for 600 volts. However, taking everything into account it would appear that in general the commutating characteristics of 1200-volt machines of the usual capacities ought to be as good as, or better than, those of 600 volts regardless of the question of interpoles.

The statement was made this evening, that it was found in general that 150-kw. per pole was about the limit of output which would be obtained with ordinary non-interpole converters. This figure agrees fairly well with those given in our paper, but attention should also be called to the fact that this rating per pole is also approaching close to the limit of cost, that is, when the output per pole goes much above this a larger number of poles can be used with practically the same cost per machine.

The point has been brought out this evening that the real field for the interpole commutator is where the loads are very intermittent and where the peaks are very high and of comparatively short duration, such as in certain classes of railway service, etc. In general I agree that it is wrong to put in a larger machine to do a certain service, simply to obtain momentary overload capacity. If a 200-kw. machine, for instance, can handle a certain average service, while a 400-kw. machine is installed simply to take the swings or peaks, then if the smaller machines can be made to take these swings by the use of interpoles, and cannot be made to do it without the interpoles, the interpoles will certainly represent an improvement in such cases. On the other hand, it must be borne in mind that in small units, such as from 200 to 400 kw., the machines would be made normally with four poles and, such being the case, then with well proportioned windings the commutating characteristics of a 200-kw. machine can be made considerably better than those of a 400-kw. relative to its normal rating; that is, the 200-kw. machine could be made to commutate almost as much total overload as the 400, while its average losses are considerably lower.

Such a 200-kw. machine could possibly be made of a somewhat cheaper construction, if its inherent commutating characteristics were sacrificed somewhat and then again improved by the use of interpoles. However, part of the gain from the reduction in the size of the machine is lost in the addition of interpoles. On the whole, however, such a machine with interpoles may be somewhat more suitable for very intermittent service than the equivalent non-interpole machine. But, when it comes to large capacity units for very intermittent service, then the use of a smaller rating machine, corresponding to the average load, would naturally tend toward the choice of a higher speed when such is possible, and the conditions result in those mentioned in the paper as being advantageous for interpoles. For instance, if a 1500-kw. machine is required for very intermittent service, in which the average load is 750 kw., then we might take a machine with a smaller number of poles than required for the 1500-kw. rating. With this smaller number of poles and higher speed, the extreme limit of commutation would naturally be lower than on the 1500-kw. slower speed size, and therefore by the addition of interpoles the commutating limit may be raised so that this smaller machine would handle the same peak service as the larger machine. In such a machine the real limit is not in the mechanical conditions, such as the commutator construction, but in the commutating characteristics, and therefore it could advantageously be made of the interpole type consistently with the conclusions drawn in the paper.

In the discussion this evening, the assertion has been made several times that the interpole type of converters will not flash any more readily on short circuit than the non-interpole type. In reply to this I will say that this is a very difficult question to determine definitely in commercial service, as it is difficult to find exactly comparable conditions. Reports which I have received from time to time in regard to 600-volt interpole converters in actual service are to the effect that the operators of the machines considered them somewhat more sensitive on short circuit than the non-interpole type, although under normal operation, and especially under heavy overloads, the comparison is slightly in favor of the interpole type. However, as stated before, it is difficult to make an exact comparison, for two different size converters, built along the same designs, will not always operate exactly alike. It seems to me in regard to this question of flashing on short circuit, that the real remedy is to eliminate, as far as possible, the cause of the short circuits. Violent short circuits on large railway systems are liable to cause troubles other than in the converters themselves and every endeavor should be made to reduce the short circuits to a negligible number. If the short circuits can be made infrequent enough, then any possible difference which there may be between the interpole type and the non-interpole type as regards flashing would be of no moment. It should be noted also, that such short circuits are confined almost entirely to railway service, while in industrial power service and in lighting they may be considered as extremely rare.

Some question has been raised this evening regarding the statements in the paper that in case of sudden overload or short circuit the alternating-current and direct-current magnetomotive forces will not balance each other and that the machine will operate momentarily as a direct-current generator, with a correspondingly high armature reaction. The basis of the criticism is that the converter, being a synchronous machine, cannot change its speed except for a very short period, namely, that occurring within a small fraction of one cycle, otherwise the machine would fall out of step. For such a small change in speed, it was argued, very little energy could be given up as a direct-current generator as there is not enough stored energy in the converter armature to give up much energy as a direct-current generator without falling out of step.

At first thought, such an argument seemed reasonable, but one answer to it is found in the operation of a synchronous converter on a single phase circuit. In such operation the energy supplied to the alternating current end *falls to zero twice in each cycle, while the direct-current output remains practically constant.* The alternating-current input must therefore vary from zero to far above the direct-current output of the machine. The converter must therefore act as a direct-current generator, for a brief period, twice during each cycle. When it is considered that such a converter can operate with more or less sparking up to three or four times full-load current, or even much more, depending upon the design of the machine, it is obvious that the converter can deliver very heavy outputs momentarily as a direct-current machine without falling out of step.

Also, a little calculation will show that with an ordinary design of synchronous converter the stored energy in the armature is such that, in dropping back as much as 45 electrical degrees in position, the armature could give up an enormous energy compared with its normal rated capacity. If it were not for this it would not be possible to run the machine on heavy load on a single phase circuit.

That is all I will say in regard to the points brought up in the discussion. However, there are several points I want to bring out in connection with the paper itself. In the first part of the paper it is stated that the ampere turns on the interpoles of a direct-current generator are always greater than the ampere turns of the armature winding. This statement is not correct in all cases but in those arrangements which depart from this rule, direct-current generators and converters would be affected in the same way so that for comparative purposes the statement in the paper may be considered as correct.

When there are as many interpoles as there are main poles it is correct to say that the ampere turns on the interpoles should always be greater than on the armature. However, in some cases, especially on small machines, the number of interpoles on direct current machines is made only half as great as the number of main poles. There are several advantages in this arrangement and they apply equally well to generators and synchronous converters. Obviously where only half as many interpoles are used the commutating flux or field of each interpole must be at least twice as strong as when the full number of interpoles is used, as the opposing e.m.f. set up by the interpoles must be sufficient to overcome the e.m.f. of self-induction, regardless of the number of interpoles. This opposing e.m.f. need not be distributed over the whole armature coil, but could be located over either side of the commutated coils or even along a short portion of its length. It is only necessary that this opposing e.m.f. should have the proper value, while the distribution of it seems to be of relatively less importance. It should be understood, however, that the use of half the interpoles is permissible only with drum-wound armature windings, where each armature coil spans approximately one pole pitch. Ring-wound armatures require the full number of interpoles.

Experience shows that when but half the number of interpoles is used the demagnetizing ampere turns, or those which directly oppose the armature magnetomotive force, should have about the same value *per interpole* as when the full number is used. However, the effective ampere turns which set up the commutating flux must be doubled in value, as just stated. Therefore the total ampere turns *per interpole* would be greater than when the full number of interpoles is used, but the total number of ampere turns on all the interpoles is much less than with the full number of interpoles. In consequence, there is a very considerable saving in the amount of copper required.

On account of the increased number of ampere turns per interpole when half the number of poles is used, the interpole leakage will be increased in proportion. This is particularly objectionable on large machines where the design of the interpole becomes difficult on account of magnetic leakage. Therefore this arrangement is usually confined to small machines.

A very considerable advantage in this arrangement is that the ventilating conditions are improved due to the fact that the interpoles and main poles do not so completely enclose the armature, for, with alternate interpoles omitted, the circulation of air between the armature and the field poles can be materially improved.

With interpole converters, with their smaller ampere turns per interpole, the omission of alternate interpoles will not have as much influence on the general design as in the case of direct-current generators. As the interpole ampere turns are only about 35 per cent as great as on a direct-current machine, and as about half is useful and half demagnetizing, it is evident that the useful component would readily be doubled, thus doubling the useful flux, while the total leakage would still be far less on a direct-current machine. Therefore the smaller number of interpoles is much better adapted to the synchronous converter than to the direct-current generator.

In the converter the use of the small number of interpoles also possesses a further advantage. In the case of a short circuit, and assuming a negative field to be set up by the armature reaction, as described in the paper, the use of half the number of interpoles would cut this reverse field to half value. In consequence, any flashing tendency would be proportionately reduced. Half the neutral spaces being without interpoles, and the other half having interpoles, it is evident that such an arrangement should be practically midway between a non-interpole and a full interpole converter as regards any flashing tendencies.

It is also evident that with half the number of interpoles the ventilating conditions will be improved just as on the direct-current generator.

The lower leakage in the interpoles of the converter allows another material difference between the design of the converter interpoles and those of the direct-current generator. In ordinary direct-current generators, especially those of large capacity, the interpoles, as a rule, are made almost the full width of the armature core, principally in order to maintain a lower saturation of the interpole core. As the width of the interpoles is varied the leakage flux varies practically in proportion to the width, but the total useful flux remains practically constant. Therefore, with wider interpoles the flux density due to the combined leakage and useful fluxes will be lower than if a narrower pole were used, and the saturation will be correspondingly reduced. In the interpole converter, however, the leakage flux being so much lower than in a direct-current generator, it is evident that the useful flux could be correspondingly increased while maintaining no higher saturation than on a direct-current machine. This, therefore, permits a much narrower interpole on the converter than on a direct-current machine. As the interpole becomes narrower than the armature the reverse field which may be set up on short circuit also should be proportionately reduced, so that with interpoles of practically half the width of the armature, the conditions should be practically equivalent to those where half the number of poles is used, as far as flashing conditions are concerned. The use of narrow interpoles should also allow better ventilation than when the full width is used. Narrower interpoles, of course, allow considerably less copper for the same total number of ampere turns. However, unless the interpoles can be made less than half the width of the armature, the amount of copper required for this arrangement would be still greater than would be required with only half the number of interpoles, each of full width of the armature.

There are many other points in connection with the use of interpoles on converters which were not mentioned in this paper. I will describe briefly a few interesting features which are encountered in the design of such machines, but which are not found in direct-current machines.

One of these concerns the application of dampers to interpole converters. It is found that the usual distributed cage type of damper supplied with self-starting converters is not directly applicable to the interpole converter. Dampers are supplied to synchronous converters for two purposes, namely, to prevent hunting and to obtain good self-starting conditions. To prevent hunting the damper should be thoroughly distributed through and around the pole face in the form of numerous low resistance bars or rods which are joined together at each end by low resistance connectors. There may or may not be any connection between the dampers on adjacent poles. In practice, with well proportioned dampers, such connection between the poles may be of some benefit, but this is difficult to determine as far as hunting is concerned. Those conductors embedded in the pole and immediately surrounding it appear to give all the damping action which is necessary if the damper is well proportioned.

However, when it comes to self-starting converters, that is, those which are started and brought up to speed by direct application of alternating-current to the collector rings, it is claimed by some designers that the interconnection between the adjacent dampers is of benefit at the moment of starting, by reducing the tendency toward dead points or points of very low starting torque. When started in this manner the armature of the converter becomes the primary of an induction motor, while the cage damper in the field poles becomes the equivalent of a cage winding on the secondary of an induction motor. It is claimed that the interconnection between the dampers to form a complete cage allows better polyphase action in the secondary winding. Any beneficial result of this should show in more uniform torque at start, but not to any pronounced extent in the apparent input required to start the converter and bring it up to speed.

When hunting occurs the magnetic field in the main poles is alternately shifted or crowded toward one pole edge or the other and the parts of the damper embedded in and immediately surrounding the pole face are particularly effective in preventing such shifting. Also, the lower the resistance and the better distributed this damper, the more effective it appears to be in general as regards damping.

On the other hand, for self starting, the damper, acting as a cage secondary of an induction motor, will have the characteristics of such secondary and therefore for best and most uniform starting torque conditions, a relatively high resistance is desirable and a continuous cage is usually preferred. In consequence, the two conditions of best damping and best starting are, to a certain extent, opposed to each other.

In the use of a continuous cage damper is found a difficulty in the application of interpoles to the synchronous converter. If adjacent dampers are connected together, as shown in Fig. 1 then the interpole between the two main poles is actually surrounded by the low resistance damper circuit, a condition which is very objectionable, as explained in the paper. Consequently, the usual arrangement of the cage damper for self starting is not advisable on an interpole converter which is subject to sudden fluctuations in load. In other words, the continuous cage damper should not be used, or its design should be modified very considerably, in the case of self-starting converters, which are subject to considerable fluctuations in load in service. If the continuous cage construction is desired, the individual dampers might be connected together by high resistance connectors.

A second interesting point in the design of interpole converters, but not found in direct-current generators, comes up in connection with the copper loss in the tap coils, that is, those armature coils which are tapped directly to the collector rings. As is well known to those familiar with synchronous converter design, the copper loss in the tap coils of a rotary is relatively high compared with the average loss in all the coils, the loss per coil falling off to a minimum value between the taps. The real limit in carrying capacity of the armature is fixed by the heating of the tap coils and not by the armature copper as a whole. It is possible to overload an armature so that the tap coils will roast out while the remaining coils will show very much less signs of heating. The heating in these tap coils also increases rapidly as the power-factor of the alternating-current input is decreased, the output remaining constant. Therefore by reducing the power-factor of a converter while keeping the direct-current output constant it is possible to roast out the tap coils. The true limit of heating in a converter armature therefore is found in these coils. Herein is found a difference bewteen the interpole and the usual non-interpole converter. In the non-interpole type, as usually constructed, the armature coils are of the fractional pitch or "chorded" type in which the "throw" or "span" of a coil is one or more slots less than the pole pitch. The primary object of this is to improve commutation. In the ordinary direct-current winding there are two coils in each slot, one above the other. With a full pitch winding, when the upper coil is being commutated or reversed the lower coil in the same slot is also being reversed so that the e.m.f. of self- and mutual-induction of the commutated coils is due to the reversal of the local field of both upper and lower commutated

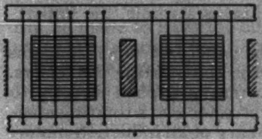


FIG. 1

coils in the slot. With a fractional pitch winding, the upper coil which is being commutated lies in a different slot from the lower one which is being commutated at the same instant.

This same arrangement of fractional pitch winding puts the upper tap coil in a different slot from the lower one so that the maximum heating does not occur in the upper and lower coils in the same slot, as would be the case if a full pitch winding were used. Therefore, with a fractional pitch winding the heating is somewhat better distributed than in the full pitch winding. However, with interpoles, a full pitch winding would naturally be used, as a fractional pitch winding would mean a relatively wide interpole with a corresponding increase in distance between the main poles. Therefore with the full pitch winding used with interpole converters the heating due to the tap coils will be more concentrated than in the non-interpole type. In other words, the machine will have less maximum capacity unless more copper is used in the armature coils, or an inferior type of interpole construction is used in order to allow a fractional pitch winding. This looks like a minor point, but when it is borne in mind that in modern converter designs the starting point in the design of the armature winding is the permissible copper loss in the tap coils, and not the armature copper loss as a whole, the importance of this point may be seen.

A third point, not mentioned in the paper but which concerns design as well as operation, is found in self-starting converters. In such machines the alternating current is applied directly to the alternating-current end of the converter and a rotating magnetic field is set up, just as in the primary of an induction motor. This field travels around the armature at a speed corresponding to the frequency of the supply circuit and the number of field poles and all the armature coils in turn are cut by this traveling field. Those coils which are short circuited at the commutator by the brushes form closed secondary circuits and secondary currents are set up by the alternating field just as in commutating type alternating-current motors at start. As soon as the converter gets in motion the short circuit is transferred from coil to coil but the short circuit current must be broken as each coil passes out from under the brushes and this results in more or less sparking, depending on the size and general proportions of the machine. It is a question to what extent this sparking is dependent upon the normal commutating characteristics of the armature winding. Other things being equal, presumably the better these characteristics the less should be the sparking and burning at the brushes when the converter is self started from the alternating-current end. On this basis then, a converter armature designed with poor commutating characteristics and in which the commutation at synchronous speed is accomplished by interpoles, should spark considerably more when starting than a converter which has inherently very much better commutating characteristics. The presence of commutating poles should in no way help commutation at start as there is no current in the interpole winding. However, as converters are started very infrequently, such increased sparking at start would probably do but little real injury. This is simply mentioned as one of the points in which the designer is concerned.

Some reference has been made this evening to the split pole converter in connection with interpoles. Some distinction should be made between the true interpole or commutating pole arrangement referred to in this paper and what is sometimes referred to as the interpole in the so-called "split-pole" converter. In the split pole converter, as usually built, there is a series of wide poles alternating with narrow poles, the field construction therefore resembling somewhat the ordinary interpole machine. In the split pole converter, however, the small pole is used primarily for the purpose of obtaining variations in the direct current voltage and not for the purpose of obtaining a true commutating field. The winding on this small pole on the split pole machine is usually in shunt with the armature instead of in series, and its circuit is so arranged that the polarity can be varied from maximum down to zero and to maximum in the opposite direction regardless of the armature current carried. In certain combinations this arrangement can be made to have the effect of commutating poles, but under other conditions it may have just the opposite effect.

The small pole is usually placed close to one of the main poles, thus allowing a fairly wide interpolar space between itself and one of the adjacent large poles and a very narrow space to the other large pole. Commutation occurs usually in the wider interpolar space and not under the small pole itself as is the case in the true interpole machine. The direct-current e.m.f. is generated by the resultant field due to one large pole and the small pole which is closest to it. When these two have the same polarity the direct-current e.m.f. is highest and when they are of opposite polarity it is lowest. However, the alternating-current e.m.f. is due to the flux of two adjacent poles, a large and a small one, of like polarity. It is evident therefore that the maximum alternating-current e.m.f. will coincide in position with the direct-current only at the highest direct-current e.m.f.; that is, when both fluxes included in one direct-current circuit are of the same polarity. At lowest direct-current e.m.f. when one direct-current circuit includes two fluxes of opposite polarity, it is obvious that the maximum alternating-current e.m.f. must be shifted circumferentially with respect to the direct-current. The alternating-current magnetomotive force will also be shifted in like manner with respect to the direct-current and the resultant of the two will vary both in height and position with variations in the strength and direction of the flux of the small pole.

At highest direct-current e.m.f. a coil which is being commutated lies midway between poles of opposite polarity and the conditions resemble those in an ordinary converter as regards commutation. At the lowest direct-current e.m.f. the commutated coil lies midway between two poles of like polarity and there will be a field flux in the interpolar space in which the armature coil must commutate. The direction of this field may be such that it will assist in commutation; that is, it will tend to overcome the higher magnetomotive force of the armature currents resulting from the alternating-current and direct-current magnetomotive forces being shifted with respect to each other, as just mentioned. Therefore this interpolar field flux may act in a very beneficial manner under certain conditions. However, if this flux is in the right direction for assisting commutation when transforming from alternating-current to direct-current, it will evidently be in the wrong direction when operating from direct-current to alternating-current. Also, this field flux in the interpolar space will vary with any variations in the strength of the small pole; that is, with any change in the direct-current voltage, although the currents in the armature may be unchanged. Also, this interpolar field may remain of constant strength, while wide changes may occur in the armature currents, and thus in their resultant magnetomotive forces. It is obvious therefore that this interpolar flux can be equivalent to a true interpole of proper strength and polarity, only under a very limited range of operation.

In conclusion I may say that, as brought out in the paper, the real field for interpoles in synchronous converters is found in connection with higher speeds and large outputs per pole. I am an advocate of the highest speeds which the public will stand, up to the point where no further real gain in cost and performance is obtained. If this highest speed in converters is such that interpoles are of material benefit, then in such machines we may look forward to the use of interpoles. However, for the relatively low speeds represented by much of our present practice the use of interpoles can be considered as only a relatively small improvement, concerning which there may be honest differences of opinion regarding the commercial value.

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TESTING STEAM TURBINES AND STEAM TURBO-GENERATORS

BY E. D. DICKINSON AND L. T. ROBINSON

Of late years an increasing amount of consideration is being given to the economic production of power, and as the cost of coal in a steam power station is the largest item of expense, it naturally follows that the efficiency of the apparatus for generating power should be high. In order to determine these efficiencies, certain accurate measurements, or tests, are necessary, and it is the intention to outline what precautions must be taken, in order that the results may not be misleading, and also to consider the relative degrees of accuracy of different methods.

The term efficiency is a fruitful source of misunderstanding. The only meaning which is of any commercial significance to the operating engineer is that which gives the ratio between the energy in the form he desires, to the energy available in the fuel. In other words, what he wants to know is, how much is he getting out for what he puts in.

There is one point that must at all times be kept in mind and that is, that all tests, even when accurate, are at best but an indication of what may be expected in the over-all economy of the station. A specific example of this is a certain European power house, which contained several engines of the best makes. When steam turbines were installed, the coal consumption was decreased about 20 per cent, though the test efficiency of the turbines showed no such marked superiority over that of the engines.

In the manufacturing of steam turbines a great amount of testing is necessary, to determine the effect of making changes in design or to verify theories and formulæ which cannot be established by calculation; much of this is of an experimental or laboratory nature. There is also a large amount of testing done, in order to establish the over-all economy of the complete unit. This latter is all that is of commercial value to those operating steam turbines. The actual efficiency of the turbine alone, is of some interest, but can only be determined by measuring the power delivered by the shaft to some form of brake, or to a generator of known efficiency. Any testing by allowing for the different losses, by the methods often employed for electrical apparatus is impractical and should not be considered.

In this paper it is not the intention to elaborate all the numerous details which must be carefully taken care of when tests are being made. Many points of importance are only touched upon. Every test must be given special consideration, and the necessary precautions to be taken will depend on local conditions.

MEASUREMENT OF THE STEAM INPUT

Weighing Condensed Steam. The one positive method of testing a turbo-generator is to measure the steam that goes in through the throttle valve, and the electric energy delivered at the terminals of the generator. The best method of determining how much steam enters the turbine is to collect and weigh all the steam after it has been condensed. This necessitates the use of a condenser of the surface type. In making such a test two things are essential: First that all the steam used on the turbine be condensed and measured; and second, that no steam or water, not used in the turbine, be allowed to enter the condenser. Should the condenser not be perfectly tight, some of the cooling water will be drawn into the condenser, and mixed with the condensed steam; this is a common source of error. The condenser should have leakage checked, before and after each test. With all steam turned off the turbine the condenser should be run for some time with full vacuum, and the discharge from the hot well pump very accurately measured.

Split condenser tubes will sometimes cause leakage which is extremely difficult to locate, and cannot always be determined by measuring the leakage. This is the case when the split opens up only when the condenser is heated with large flows of steam. This action will generally give erratic results, and no tests should be considered that do not show consistency with other tests on the same machine.

Measuring Condensed Steam. The most accurate method of measuring the condensed steam is by the use of tanks, so arranged that all the water can be weighed at equal time intervals during the test. The pump, piping and tanks must be free from leaks, and the condenser and pumps must be so arranged that the water will continuously flow to the pump, this is essential in order to get accurate results.

Weighing Water Fed to Boilers. This method is quite frequently resorted to when the condensed steam cannot be measured, as is the case when the turbine is operating non-condensing, or when the condenser is of the jet type, in which the cooling water is mixed with condensed steam. In making such tests, the liability to error is very great, and every precaution must be taken in order that the results may be considered reliable within any degree of accuracy.

The steam piping connecting the boilers and turbine must be disconnected from all other piping, and all openings must be blanked off; valves must not be relied on. All blow off and drain valves must have their outlets visible. All piping between boiler feed-pumps and boilers must be exposed, and have no branches. Leakage of the boiler itself is the most difficult to locate, as all water or steam escaping is vaporized and carried up the stack. The boiler leakage should be checked before and after each test by closing the throttle to the turbine, or if necessary blanking the pipes at the turbine and running a test measuring the amount of water required with full steam pressure on boilers and piping. The feed water used should be weighed, and not measured by meters.

Tests which have come under our observation have shown boiler leakage of 10 and 12 per cent of the water weighed into the boilers, and one particular case showed a leakage of over 20 per cent.

Test by Heat Balance. This method of testing is based on measuring the amount of heat transferred to the cooling water from the condensed steam. It is extremely inaccurate and unreliable, and at best can give but an approximate idea of the quantity of steam being condensed. The quantity and temperature of cooling water and the temperature of the outgoing water, carrying with it the condensed steam, are measured as accurately as possible. The reason for inaccuracies is the difficulty of measuring the quantity of cooling water and its true average temperature change. The temperature of the cooling water may vary at different sides of the pipe, and small discrepancies in the reading will show large variations in the estimated steam consumption of the turbine, since the temperature rise is small.

Duration of Tests. In order to establish accurately any given point, all tests should be run with fixed conditions after a state of equilibrium is established and things are constant for an appreciable length of time. The time required will depend on the nature of the test being made. In general, when small amounts are being measured, the duration of the tests should be somewhat greater, for example, when measuring the condenser leakage, this test should be run for a sufficiently long period in order that the small quantity of water which will come through may be accurately weighed.

Efficiencies. The net over-all efficiency expressed by the ratio between the kilowatt hours output of the generator, and the available energy in the steam, is the only one of any particular commercial value. The comparison of efficiencies of different machines is the most satisfactory way of considering their relative merits. To determine the available energy in one pound of steam it is necessary to know the pressure in pounds per square inch, the quality and the temperature of the entering steam; also the pressure at the turbine exhaust. To measure the exhaust pressure, or vacuum, a gauge should not be relied on. The most accurate means is to use a full length mercury gauge, and subtract the readings given by this, from the atmospheric pressure at the time the test is made. If the steam be superheated, since there is some difference of opinion concerning the specific heat of superheated steam, the figure assumed must be given.

In testing turbines consisting of several stages, the pressures in the different stages should be measured, this affords a check, and should show any abnormal conditions existing in the interior, which might not otherwise be observed.

The kilowatt output should be net, that is, the kilowatts for excitation should be subtracted from the generator output.

Checking Instruments. All instruments, including meters, gauges, thermometers, and scales must be very accurately calibrated or checked before and after the test. Small inaccuracies in some of the readings may entirely discredit tests which have cost a great deal of money to make.

Inspection and Adjustment. Before tests are made the turbine should be inspected to see that all parts are in proper condition. If necessary the interior should be examined to see that the buckets have not been damaged by foreign substances, and all necessary adjustments made at this time. After the tests have been completed, the machine should be ready for commercial service, and no adjustments of the turbine should be made.

Corrections. Whenever possible, turbines should be tested under the conditions for which they were built to operate. Correcting for different conditions is always liable to throw some doubt upon the accuracy of the test, and therefore on the efficiency of the machine being tested. Different machines will have different correction factors for varying conditions, and for this reason it is impossible to arbitrarily fix the allowances that should be made.

In general, the corrections for steam pressure, moisture, or superheat, are less liable to be misleading than that for varying vacuum, for the reason that comparatively large changes in any one of the first three, will but slightly affect the conditions in the machine; whereas, a slight change in the vacuum makes an enormous change in the available energy and volume of the steam in the low pressure end of the turbine. A turbine may show a splendid efficiency with poor vacuum, but unless it be properly proportioned, it may give a poor efficiency with a good vacuum.

Test Results. The majority of commercial tests on turbo-generators are made to determine whether or not the unit is fulfilling the guarantees made by the manufacturer of the apparatus. The steam turbine differs from the reciprocating steam engine, in that it is impossible to take any readings that will give a direct indication of the power being developed. The designing engineer with all necessary data, can estimate very accurately what power the turbine is developing under any given set of conditions. But the operating engineer has not the time, nor is he interested in making such calculations.

It will be apparent from the foregoing, that the complete test of a unit, necessitates taking a large number of measurements, and small inaccuracies in taking many of the readings are liable to affect considerably the final results. For this reason, it is obvious that no machine should be discredited on account of small variation in the final results.

With the high efficiencies now being obtained, small inaccuracies in readings will show a relatively large per cent variation in the steam consumption. It is for this reason that manufacturers guarantee an efficiency which is not quite so good as may be expected from the unit. Another method is to guarantee the efficiency that may be expected, with an allowance to cover permissible inaccuracies in making tests.

The Steam Flow Meter. Under suitable circumstances, thoroughly accurate tests may be made by measuring the steam with a meter. Such tests will be more convenient than those made by any other method. Certain precautions are necessary, but there should be small expense in providing conditions that will insure reliable results with the best meters.

Even where other methods of measurement are used the steam flow meter will always be a valuable adjunct since its readings are accurately proportionate to flow and show the conditions instantaneously.

MEASURING THE ELECTRICAL OUTPUT IN CONNECTION WITH TURBINE TESTS

The output of the turbo-generator may be either direct current or alternating current. We will consider first the measurement of direct-current output. Usually, station instruments in connection with generator switchboard have been provided, but unless temperature conditions can be very accurately controlled and the instruments can be checked under operating conditions they should not be used. The station voltmeters may sometimes be satisfactory but it is the usual practice to supply direct current station ammeters to operate from shunts of approximately 60 millivolts drop. This requires that the indicating part of the ammeter be largely a copper circuit; therefore the whole combination is subject to considerable error due to variations in room temperature, and with some shunt arrangements, to variations in the current to be measured as well. For the precise measurement of direct-current output, portable indicating ammeters should be used having 200-millivolt-drop shunts,* and, therefore, permitting the use of indicating millivoltmeters whose circuit consists largely of resistance material having practically no temperature coefficient. It is also desirable, when possible, to measure the volts by similar portable voltmeters.

When using either switchboard or portable instruments the influence of any stray fields should be investigated and arrangements made whereby these stray fields will not affect the measured output. Special caution must be observed in this respect if the instruments are not of a shielded type. If the influence of stray fields is very small it may be eliminated from the final result by periodically turning the instruments between successive readings. There is also another point in connection with the measurement of amperes, especially when testing large units, which is important, namely, care should be taken to correct the observed indications of the millivoltmeter for any electromotive forces that may appear in the shunt or leads due to thermo-electric effects. The amount of error due to this cause may be observed by reading the millivoltmeter at the close of the test with no current flowing in the main circuit. There may then be observed a small positive or negative indication, which should be applied as a correction to the observed ampere readings. Of course, to have this correction constant throughout the test the entire arrangement should be run under the test load until final temperature conditions in the shunt have been established. This precaution need not be observed in connection with standard precision shunts having 200 millivolts drop.

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* This is not an arbitrary value but has been chosen by several makers as giving the best compensation of all temperature errors.

Referring again to the station type of shunts, unless the ammeter is checked with the shunt connected into the bus bars, great care should be taken to know that the distribution of current flow through the shunt is the same when the ammeter is used, as when it was tested. It is quite possible to have large errors due to this cause.

Measurement of Alternating-current Output. If the output is small—less than 20 or 30 kw.—wattmeters, ammeters and voltmeters without current or volt-multipliers may be used. The same remarks with regard to disturbing influences, which apply with direct current instruments apply with even greater force to instruments for alternating current. They are not usually much affected by steady magnetic fields but in many locations where large generators must be tested there may be fields which would have an appreciable effect on the indications of the instruments and which would alternate with the same frequency as the circuit to be tested. The current leads of the circuit under test may become a source of error. Such fields require the use of shielded instruments or the careful handling of those of the unshielded sort to eliminate any possible errors.

After all questions in connection with the instruments themselves have been disposed of it is necessary to consider the proper use of the instrument transformers which provide usually the only means of enlarging the capacity of the instruments to meet ordinary requirements.

The station equipment provided for use with the generator can be checked carefully and both the instruments and transformers employed for the precision test, but this is not usually as convenient as to insert transformers specially tested for the work. Of course, if the constructors of the plant have the foresight to install tested transformers these are, at any time available, for precision testing. Makers of instrument transformers can supply them when requested with certificates showing performance under any specified conditions.

In using instrument transformers it is necessary to observe the precaution to have the secondary connected load the same as that which was on the transformers when they were tested for the certificate. It is also necessary, if the test is to be made under conditions that will give low power-factor on circuits, to at least know that the phase displacements in the instrument transformers are not large enough to appreciably affect the results. It is also well to observe the precaution not to use instrument transformers with interconnected secondaries except for the common ground connection. This should be employed as a safety precaution.

If possible, a test should be made on non-inductive load. If this is done the indications of the voltmeters, and ammeters, may be used to check the indications of the wattmeters. If all the test arrangements have been satisfactorily attended to the apparent power as showed by the volts and amperes should agree within one per cent with the wattmeter indications and the watts indicated should be taken as the true output. If the test cannot be made at unity power-factor, the voltmeters and ammeters should still be included so that the general conditions of distribution of load etc., may be known throughout the test. For this purpose the station instruments would be satisfactory.

The use of watthour meters for this class of testing should be avoided wherever possible. There are watthour meters for direct-current and for alternating-current circuits, and under both of these headings there are those which might be classed as accurate and those which could hardly be so described. Still the very best watthour meters that can be made are inferior in performance to the best portable indicating instruments. Watthour meters are slightly affected by changes of voltage, frequency, wave shape, etc., and by the amount of load current which is being measured. Sometimes if the test must be made under service conditions and the load is very fluctuating the output may be more accurately determined by watthour meters than by indicating instruments, but this would represent extreme conditions, and would not usually be true.

Watthour meters should never be used unless checked in place at the frequency, voltage, wave shape, etc., which are to be used in testing. If it is not possible to run a complete test on a fairly steady load it is usually possible to make a few runs on the watthour meter under load conditions and to use this check as a basis for determining the output by means of the watthour meters during the test run on unsteady load. It is still advisable to read the indicating instruments at short intervals so that their indications may be made use of in computing the final result. The fluctuations shown by the recorded values will determine how much weight should be given to the indicating instruments.

Checks of watthour meters should not, for precision purposes, be made with the meter subjected to other than exact load conditions and on the same circuit. If watthour meters are tested in place, using the above precautions, and indicating instruments are employed and read at frequent intervals during a test run of three to five hours, the watthour record should agree with the output as determined by the indicating instruments within one per cent on fairly steady commercial loads with the chances largely in favor of the indicating instruments being correct. Single-phase indicating instruments for polyphase service are to be preferred for precision work to polyphase instruments, for the obvious reason that indications of a polyphase instrument are made up by the two elements in such a way that it is not possible to apply corrections to either element to get the true total result unless the division of load is known by single phase instruments; and if the single phase instruments are required for this purpose they may as well be of the precision class and used for the actual determinations, and the polyphase instrument omitted.

Conclusion

To accurately and positively determine the efficiency of a steam turbine, great care must be taken in making the tests. If all necessary precautions are not taken, the results are liable to be misleading, and will in all probability be absolutely valueless so far as determining the actual economy of the unit.

The modern steam turbine, unlike the reciprocating engine, should require no adjustments before making economy tests, that is, after it has been adjusted, any turbine should be able to stand all the sudden variations of load and steam conditions occurring in commercial operation. The turbine should be tested with the adjustments that are normally maintained. After tests have been made to establish the economy of a turbine, no adjustments that may affect the efficiency, should be made. Any such adjustments may discredit the entire test.

The testing of steam turbines in some respects resembles the testing of water turbines, and it is recognized what precautions have to be taken in testing them in order to avoid misleading results. The testing of steam turbines demands even more care, owing to the greater number of conditions which have to be maintained and accurately measured.

With the ever increasing search for higher economies in the production of power, the efficiency of every piece of apparatus that forms a link in the chain between the coal pile and the switchboard must be maintained at its best, and in a turbine power station it is not sufficient to know the efficiency of the turbine alone, but every source of loss should be run down and eliminated or reduced to a minimum. Several small losses may in the aggregate be sufficient to cause an otherwise economical plant to make a very poor showing.

DISCUSSION ON "TESTING STEAM TURBINES AND STEAM TURBO-GENERATORS", NEW YORK, DECEMBER 9, 1910.

Gano Dunn: Although it recognizes in full the necessity of manufacturing tests, the paper deals principally with over-all efficiency tests largely as acceptance tests. Before acceptance tests come to be necessary—in fact before the manufacturer can know what he may guarantee—there must be an enormous amount of detail testing and of research testing, both of the generator and of the turbine.

The latter tests, from an engineering and certainly from a scientific point of view, are more important than acceptance tests, and I had hoped to see in the paper more data on the segregated tests of the generator itself and of the turbine itself.

In respect to innumerable details, the design of the generator is essentially a result of what previous designs have done and in a piece of machinery of high speed and difficult arrangement of parts such as a turbo-generator, tests are more necessary than in any other kind of similar electrical apparatus, because so large a part of the design is empirical.

This is also true of the steam end of the combined unit and as I see Mr. Emmet here and remember conversations with him on steam tests, I feel that as the American Institute of Electrical Engineers, we are more interested in the research portions of the tests on steam turbines and on turbo-generators, than in the commercial portions.

When speeds are pushed beyond limits with which we are familiar, we reach a point where a further increased speed is no longer merely quantitatively different from the speed we have been using; a qualitative change takes place in our conditions and it is no longer safe to exterpolate.

It is found, for instance, when retardation tests are made on turbo-generators, that the losses from vibration, windage and eddies after certain critical values, do not follow the laws of variation that they follow below these critical values and some of them are quite erratic in the way their rate of variation is related to the variation of speed.

Since in turbo generators these losses are proportionately much larger than in ordinary generators, and since in dealing with them we are, so to speak, in a strange country, we are particularly in need of research tests.

To cite an instance, the designer of an ordinary generator provides for windage to cool the parts of his machine and he busies himself with considering only how much air will be thrown.

The designer of a turbo-generator finds such an enormous increase in the power consumed by windage that the air itself is increased in temperature, so he has to consider, not only how much will be thrown, but how much it will be heated in the course of throwing.

The increase of its temperature is so dependent upon the shapes of passages and the volume of chambers in the interior of the machine, that prediction of this increase is practically impossible at present.

In respect to balance, it is well known that below the first critical speed, if a turbo-generator is run in flexible bearings and a piece of chalk is made to approach the revolving periphery, it will first hit and make a mark on that side of the revolving mass which is the heavier, and to secure a proper balance a balancing weight must be put opposite the chalk mark.

It is also well known that above the first critical speed when the apparatus may be regarded as ceasing to revolve around its axis of figure and is gyrating around its axis of gravity, the place where the piece of chalk will hit will theoretically be rotated 180 degrees from the first place.

Under these conditions the balancing weight must be put at the chalk mark.

In the range of speeds between the limits I have mentioned the balancing weight must be put somewhere between a point 180 degrees removed from the chalk mark and the chalk mark itself.

It looks as if the working out of a law of these mass vibrations, was simple, but the flexible bearings in which the rotation must occur, impose complicated conditions, and the beautiful formulas of the ordinary laws of forced vibrations do not seem to hold.

In the works of a celebrated European company, distinguished for the success of, among other things, its turbo generators, the study of balance has been thoroughly pursued, and incidentally I might mention every turbo-generator, is balanced by a member of the Board of Directors.

This member of the Board said to me that he had worked out a formula which indicated that the position of the chalk mark lagged behind the position of the heaviest region somewhat in the way current lags behind electromotive force in an alternating circuit. This formula guided him in the calculation of the amount of this lag and the position of balancing weights and enabled him to secure the beautiful balances which characterize the apparatus of his company.

Tests and research work on questions like these are greatly needed.

Where a manufacturing company builds both the steam turbine and the turbo-generator its responsibility is of course, based upon the ratio of the electrical energy developed to the steam consumed and segregated tests of the generator and of the turbine are not essential for acceptance tests, but a number of companies make steam turbines only and other companies make turbo-generators only.

Here segregated tests are necessary to determine each manufacturer's share of the over-all responsibility.

The principal value of the segregated tests are in the reaction upon design of the laws and constants the testing discovers, and when we realize how qualitatively different many of the phenomena in turbo-generators are from similar phenomena in ordinary generators, we realize the particular need of research tests in the turbo class of dynamo electric machinery.

I hope much will be brought out in the discussion on the subjects of eddy current losses, windage losses, mechanical losses due to vibration, and the practise of balancing, all of which are so different under the high speeds of turbo-generators that they fall outside of ordinary experience and the mass of data that has been collected from it.

W. L. R. Emmet: One matter which Mr. Dunn has brought out relates to the relative value of the test of the part and of the whole—that is, he suggests, as I understand, a separate study of the generator and of the turbine.

This is very desirable, but in the case of turbine and turbo-generator units it is extremely difficult; and the only thing which can be really thoroughly investigated as a rule, is the net result.

The turbines should be sold on a basis of net result, and the net results should be really the test of the ability of the engineer who has made them, and the value of the apparatus. The reason for this difficulty is that the generator is a very high-speed piece of apparatus requiring a large amount of power, and cannot well be run by anything but the turbine which drives it. If this generator could be thoroughly investigated and evaluated on its own merits, it would be highly desirable; because there are many unknown and obscure conditions in these generators which pass muster as parts of a satisfactory general result.

We have tried very hard to investigate the generator alone, and there is one method of so doing which I believe was first carried out in our works, and which has a good deal of value. It is what I call the "deceleration"* method of testing. This consists in bringing the generator—by any means, as a motor or otherwise—to a speed in excess of that at which it is to be operated, and then allowing it to decelerate, noting the rates of deceleration and from these rates, with a carefully calculated moment of inertia, determining the amount of power exerted at any particular instant.

By so operating a generator, the power required to drive the machine at any instant in the process can be determined, and the process may be repeated with different degrees of excitation and other possible variations.

I use the word "deceleration" as it is part of the language spoken in Schenectady. I do not think there is such a word in the dictionary, in reality, but you will probably all understand what I mean.

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*For a criticism of the word "deceleration" see communication by C. O. Mailloux on page 44 of these PROCEEDINGS.

It is extremely important, no matter what methods of investigation are used on the generator, to take nothing for granted in the matter of generator efficiency in a high speed unit. That is, if somebody guarantees a certain result on a turbine generator shaft, and gives a list of losses, such statement should be accepted with great caution. The losses in high speed generators are very much greater in many cases than are generally supposed.

The windage losses are extremely large and very variable, and they vary greatly owing to the way the air passes through the machine, much power is concentrated in a small space, and there are various losses incident to leakage fluxes, and eddy currents, which often do not occur in other kinds of apparatus. There are also very large load losses; that is, I mean losses caused by the existence of large currents in the conductors which cause unequal distribution of flux in the neighborhood of the slots, and consequent eddy currents in the iron and sometimes in the field windings.

All of these conditions make it desirable to test the unit as a whole, and in fairness to manufacturers this testing the unit as a whole should be made justly and carefully, and I think Mr. Dickinson's and Mr. Robinson's paper gives a fairly complete list of the precautions to be observed.

There is one matter I want to mention which is only slightly alluded to in this paper and which I think is of a great deal of interest, and that is the steam meter. We have been using steam meters in all of our turbine tests for a long time past, and at the same time have been weighing the condensed water. We have checked results within two per cent in practically every case, and in all cases where the conditions were accurate and uniform and well understood, it was generally within one-half of one per cent.

A steam meter is a very valuable piece of apparatus and those who have used it will depend upon it and use it more. In any test it may give valuable indication which will prevent error; for if not trusted as a source of information, it will at least give a gauge on relative proportion of values.

Very often in steam tests there are obscure sources of error. In one case in the testing of a turbine near Boston, a radically wrong result was obtained—or it seemed entirely wrong, and I observed that the slope of the load curve was such as to indicate leakage. They tested the condenser and found no leakage; with a high degree of vacuum on the condenser, it was found, however, that when the steam blew into the condenser in considerable quantities it leaked badly as the pressure and the heat of the steam caused certain tubes which were split to open, so that circulating water came out and was added to the condensation which was being measured.

Francis Hodgkinson: In reading the portion of this paper covering tests on the steam ends of turbine units, I fail to see anything brought out in the way of necessary precautions to be taken, which are not well known, and are practiced by any self-respecting station engineer, undertaking the work of conducting a test. Doubtlessly, no precaution that leads to accuracy is too trivial to be neglected.

In the case of tests where the condensate is weighed, it is not difficult to obtain dependable results. The leakage of the condenser must be carefully watched, however, and sometimes as Mr. Emmet has remarked, peculiar leakages from split tubes may develop, which exist when the plant is in operation, but curiously sometimes, do not show themselves during an ordinary condenser leakage test.

In the case of tests where a jet condenser is used, or a non-condensing turbine is installed the only means available, of determining the steam consumption, is to measure the feed water. The difficulties are much greater, rendering it necessary to tear down feed pipes, steam lines, blow-offs, etc., to insert blank flanges. This frequently causes a disorganization of the whole plant, but it is nevertheless a necessity if the test is to be dependable. Nothing should be taken for granted. Every connection should be investigated. In the event of contemplated tests, the builder who demands these precautions for the sake of accuracy, is likely to find himself rather unpopular.

One point which we think might have added considerably to this paper, would have been to set forth an opinion as to the proper duration of tests. In the case of weighing the condensate true results may be obtained with a test of one hour after conditions have settled down. Nevertheless, in the case of a formal acceptance test, two or three hours at least, would generally be employed, and it will usually be found that one hour closely agrees with another. In the case of weighing the feed water, the test should certainly be for not less than eight or ten hours, at any one load. This, of course, is made necessary by the difficulty in determining the height of the water in the boiler. We all know that on blowing down the gauge before making an observation as to the height of the water, you will find the level will go up, due to the difference in temperature between the water in the glass, and that in the boiler, and there are other things which will vary the height of water in the boiler, by changing the rate of firing.

Some reference is made in the paper to what is called a heat balance test, measuring the quantity of cooling water supplied to the condenser, and noting the rise in temperature of the same. I do not think anybody would look upon this as a reliable means of determining the steam consumption of a unit, because such a small error in the temperature of the water would influence, so greatly, the amounts of steam calculated therefrom. There is, however, a possibility, with extreme precaution and using condensers which cause a high thermal rise of the condensing water, to derive fairly satisfactory results in a test of this nature.

One of the most important things which I find in the conducting of turbine tests, is the proper reading of the vacuum. One not infrequently finds mercury columns located some distance from the chamber where the vacua is being observed. These are sometimes connected by a small pipe, perhaps containing loops, which together with capillary action, will seriously interfere with the reading of the mercury column. The mercury column should be connected with as short a pipe as possible, and of sufficient size to absolutely preclude any capillarity. These same precautions, of course, apply also, to reading the lower steam pressures within the turbine, which approximate atmospheric pressure, or less, but do not necessarily hold for the high pressures. In the case of the mercury column, the barometer should preferably located alongside of it, so that the temperature correction will only apply to the inch or so difference between the barometer reading and the column reading, which may then be ignored. When great accuracy is demanded, it is as well to have a quantity of the mercury weighed in a chemists laboratory, as I have known a higher vacuum reading to have been obtained by the amalgamation of the mercury with some tin, somewhat to the enhancement of the condenser performance.

I do not feel competent to discuss that portion of the paper referring to the electrical instruments. In my experience in testing turbines in the builder's works, I was very glad when I succeeded in devising a hydraulic brake, by means of which, the question of the electrical instruments was eliminated, together with the delays required for the water rheostats and the like to become settled. By means of the brake, the load may be applied as quickly as desired, and all the refinements of observation are to know the radius of the brake arm, measure the speed of the turbine, and the reaction of the brake arm on an ordinary weighing scale, none of which call for any particular skill.

In all acceptance tests which are carried out in the purchaser's plant, it is necessary beforehand, for the builder to come to some agreement with the purchaser, as to what corrections shall be made for deviations from the contract conditions. The introduction of corrections is as objectionable to the builder, as to the purchaser, and is the more embarrassing because the purchaser is more or less compelled to accept whatever corrections the builder insists are proper. Protest on the part of the purchaser may be met with the contention that the matter of corrections is entirely in his hands, and may be entirely eliminated if he will but conduct the tests under the conditions recited in the contract. However, this is not as serious as might seem.

There should, generally speaking, be no necessity for making corrections on account of pressure. It should be easy for the purchaser to maintain the contract steam pressure, within five pounds either way, the effect of which deviation should prove negligible.

Superheat and steam quality cannot be controlled, but this is the only correction which need be determined beforehand, and there is but little diversity of opinion as to what the superheat correction should be. In steam quality, it is usual to allow 2 per cent for each 1 per cent of moisture, because of the friction caused by the presence of the water.

In the case of the vacuum correction, however, this is a variable factor, depending entirely upon the inherent design of the turbine. Where the purchaser is unable to maintain the vacuum called for by the contract, I have always arranged to determine the vacuum corrections directly from the tests themselves, by running a series of tests at different loads with the highest vacuum obtainable, and a set of similar tests at like loads with 1-in. or 2-in. lower vacuum. From these results, the proper vacuum corrections may be determined—these corrections, of course, being greater at the fractional loads. In all cases, a series of not less than three tests at different loads should be run under the same operating conditions, in order that the results may be plotted on cross-section paper, when any discrepancy or disagreement will immediately become obvious, bearing in mind that the total steam consumption of any turbine, no matter what its design may be, follows a right-line law up to the point where any by-passing or changing of areas in the turbine is resorted to. The plotting of pressures to load, and to total steam, may be a means of discovering the cause of a discrepancy.

W. L. Robb: In general I agree with the methods of testing recommended in the paper. On a few points, however, my opinion is somewhat at variance with the authors'. I agree with them that the steam conditions during test should be as near as possible the conditions under which the turbine is normally to operate in service; but I would go one step further and have the generator loaded during test with a load of approximately the same power factor that will be met with in the normal operation of the plant. Such a load will be the one most easily obtained for the test under ordinary circumstances. A test with a load of unity power factor, when under ordinary operating conditions the power factor will be much less, does not give a purchaser the desired information.

All instruments on whose readings the calculation of efficiency are finally based, should be calibrated before and after the test. My experience has not given me such confidence in series transformers that I would be willing to make any exception in their favor as recommended in the paper.

Neither steam flow meters or watt-hour meters should be used as a basis for the final calculation of the efficiency of the set. It will be found convenient, however to have both instruments in service at the time of the test. Frequently some irregularity in operation or in conditions of test, will be indicated more promptly by these instruments than from the periodic readings of the indicating wattmeters and the weights of steam. Much time may be saved in the test, from the prompt correction of troubles. At the completion of test, data will be available for determining the accuracy of the steam flow and watt-hour meters.

There are a few points that have been impressed on me by my own experiences in testing steam turbines that may possibly be worth mentioning.

The time to prepare for a test is before the turbo-generator and its auxiliary apparatus, including steam piping and switchboard are installed.

A few extra valves of relatively small cost will greatly facilitate blanking off the apparatus under test from the rest of the power house equipment, and no test is worthy of the name if reliance is placed on all valves being tight.

Little if any attention is usually given in switchboard design, to making provision for the introduction in the circuits of standard series transformers or instruments, either for use in efficiency tests or in calibration of switchboard instruments. A slight and inexpensive change in the design of the disconnecting switches now commonly installed, would greatly facilitate the use of standard instruments at times when their use is desirable.

Measurements of feed-water are unreliable as the quantity of water in the boiler is usually determined by the height of water in the gauge. The height of water in the gauge is not only a function of the quantity or weight of water in the boiler, but also of the temperature of the water and the rate and point from which the steam is taken from the drum.

A turbo-generator should of course be tested at fractional and overloads, as well as at full load. A study of the efficiency at various loads will indicate whether the capacity of the turbine and generator have been properly proportioned.

I have always found it convenient during test to work up data as rapidly as possible, to enable one to plot the steam flow as a function of the kilowatt output, selecting scales that would give approximately a forty-five degree slope to the line. Any irregularities occurring during test, such as abnormal leakage in the condenser, will be apparent in irregularities in the points on this line, and much time will be saved in removing the causes of these irregularities.

I have always made it a practice to work out the results to be obtained from observations every fifteen minutes and to eliminate in the final calculation all observations taken before the results obtained for successive intervals became uniform. This has usually meant the elimination of the observations taken during the first hour, and sometimes during the first two hours. A run of one hour after the conditions have become constant, will give sufficient data for a calculation of the efficiency, provided a surface condenser is used. A much longer test would be required if the steam consumption was obtained from a measurement of the feed-water.

When all possible precautions are taken, all instruments, both mechanical and electrical are calibrated, the steam supplied under approximately normal conditions, and the load on the generator has approximately the normal power factor, I believe that results can be obtained that are correct to within one per cent.

Edwin D. Dreyfus: The subject of the evening's paper is not only an interesting but a timely one. It is a phase of engineering work on which a great deal may be said regarding actual experience obtained and expedients and methods employed to vouchsafe very accurate and reliable results.

It is to be remembered that there are now over 2000 steam turbines in operation in this country, which has permitted us to have acquired close and quite intimate familiarity with this type of prime mover, as well as to learn the best methods of examing its characteristics. Consequently, I cannot accept the same pessimistic view as the authors, placing somewhat in question the ability of engineers in general to definitely and positively determine within very small limits of error the true performance of a turbine and its component generator.

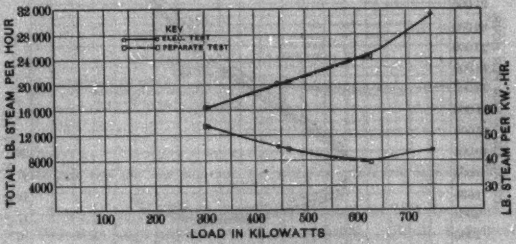

FIG. 1.—Efficiency test, 600-kw. turbine—120 lb. steam pressure, 7 lb. back pressure, 3 to 6 deg. fahr. superheat

While I fully subscribe to the precautionary measures laid down by them, it seems to me their definitions have to the casual observer the complexion of being unduly apprehensive and are unsupported by any reassuring statements in this direction.

I am able to present some evidence that I believe shows that tests should be no matter of uncertainty and that by exercising the usual care, remarkably consistent results may be obtained.

First of all, proper development in the turbine art requires that the designers and manufacturers of turbines carry out very complete tests in their own shops. For this purpose, special test floors are provided and the surface condenser and hydraulic dynamometer, involving simple formulae, are used. Obviously, some of the large turbines may be tested to only about one-half load on account of the heavy draft on the boiler plant of the works.

Fig. 1 includes tests on a 600 kw. non-condensing turbine made independently on both the turbine and the generator by brake and separate loss methods respectively, and the results combined, and then assembled and tested as a unit. The first series was conducted in conformity with the usual practice at the builder's works, and the second set were the over-all witness tests which had been specified by the purchaser. The check between the two is, of course, very gratifying, but it is just as should be expected with the necessary care and experience.

Witness tests for the U. S. Government on the two different machines of 1000 kw. capacity and of the same design, are shown in Fig. 2, for identical operating conditions. These results are, in every measure satisfactory (the normal variation being 2½ per cent) as it is to be remembered that they were run individually, and the small variation is only such as one would expect, for the dual reason—the probable slight difference in the construction of the two machines built from the same pattern, and small personal errors in observations. The foregoing tests were made with all special facilities at hand in the shops.

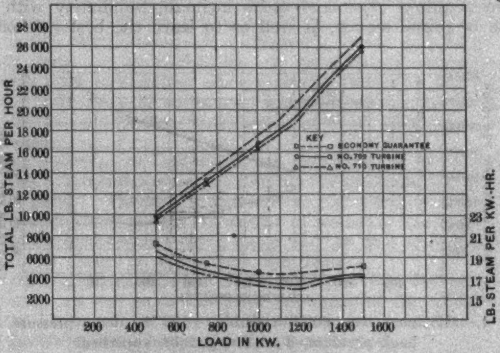

FIG. 2.—Test of 1000-kw. turbine, 3600 rev. per min.—150 steam pressure, 100 deg. fahr. superheat, 28-in. vacuum. (30-in. barometer)

Coming to Fig. 3, we have an example of three 10,000-kw. turbines at the Brooklyn Rapid Transit Company, tested after erection by the owners. At full load, the maximum variation from the mean is somewhat less than 1 per cent, which shows forcibly the degree of accuracy obtainable, bearing in mind that these three tests pertain to different machines. It also exhibits the uniformity of construction according to a given design that has been secured, which is undoubtedly more noteworthy than it would be for the reciprocating engine. One point in the test of Unit No. 7 (150 per cent load) departs appreciably from the values established in the other two machines. There is no plausible explanation for this discrepancy, but as it is the only appreciable deviation out of fifteen load tests, it should not be taken seriously. Moreover, these turbines naturally have quite a flat over-load characteristic, as the heavier loads are obtained by opening more nozzles on the high pressure wheel by means of a secondary valve, (by passing no active part of the turbine.) Mr. C. E. Roehl, the Company's electrical engineer, under whose supervision the tests were made, would I believe, be willing to make these data available to the Institute if requested. These particular 10,000-kw. turbines were the first of the double-flow design built in such capacities and are, therefore, operating at lower speeds than used in the latest practice. Higher speeds are, of course, beneficial to economy.

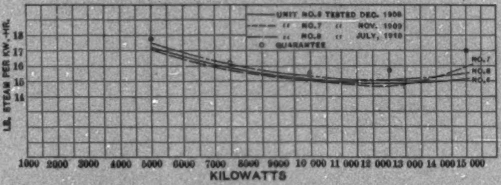

FIG. 3.—Test of 10,000-kw. turbines—corrected to 170 lb. steam pressure, 100 deg. fahr. superheat, 28-in. vacuum. (30-in. barometer)

The value of the Willans right line law applying to turbines, has already been noted by a previous speaker, as well as the characteristic line of the throttling turbine in which the inlet pressure varies directly with the load. These features prove very important in the absence of an "exploring device" like the steam indicator for the reciprocating engine. By means of these virtues, the results for any given load which may not be satisfactorily maintained for operating reasons, may be conveniently and accurately interpolated or extrapolated from the other available tests.

It has been found in most of the throttling governed turbines that the total steam line continues rectilinear until the first stage inlet pressure reaches within 10 lb. of the throttle pressure, when the curve deflects slightly upward, on account of the secondary admission valve opening at this time.

In the case of the Brooklyn Rapid Transit turbines above referred to, this occurred between 5 and 10 lb. It is to be understood, of course, that the same pressures, superheat and vacuum are maintained over the entire range of load. The value of the pressure characteristic is very well exemplified in one instance where the horse power of a turbine was calibrated against the first stage inlet pressure. This furnished a measurement of the power applied to marine reduction gear, and its efficiency was then obtained by determining the delivered work with a hydraulic brake.

Through some misunderstanding or oversight, a set of observations may show fallacious results and this important right line law immediately disproves them by their failure to rationalize with respect to others that prove themselves to be regular. Hence, there must be an element of doubt in regard to a single load test, and it is consequently entitled to no especial claims unless verified conclusively by several parallel tests in nowise connected with one another. Unfortunately such commendable practice is so frequently violated that we often find our engineering proceedings inflated with more or less doubtful information.

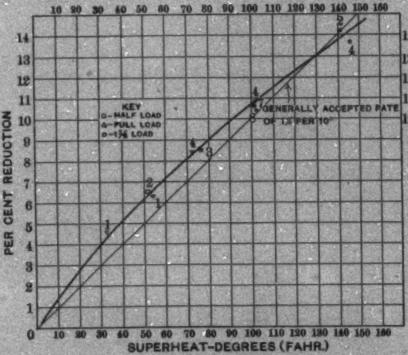

Fig. 4.—Approximate reduction in average steam consumption with varying degrees of superheat (average of 32 tests at practically the same vacuum—number of superheated steam tests indicated by figures on curve).

A word may be said for the graphical recording instruments. While they are not very sensitive from a scientific standpoint, they establish a very valuable index of any change of events during a test. And it might be possible, by their use, to discover the reason for any discrepancy that may appear in the final plot.

An understanding must be had in regard to correction factors for reducing the observed values to contract or designed conditions as has already been discussed. Different constants for pressure correction are employed, but ordinarily this is a very small factor. One company uses about one-half of the theoretical change, that is, one-half per cent for every 10 lb. For determining the variation due to changes in superheat, I recently went over the tests of a great many turbines of 500-kw. size selecting those which had been made under practically the same conditions, and found the curve of the nature shown in Fig. 4. Size should not influence the factor materially and the accepted correction of 1 per cent for 10 per cent variation is thus substantiated for ranges of superheat which are now found warranted. Similar superheat determinations were published in the September 30, 1910 issue of the ***London Engineer***, applying to a Brown-Curtis marine turbine and having the same drooping tendency. This characteristic is evidently natural as the delay of the "dew point" in the turbine occurs in a less degree for equal increments of superheat in the higher than in the lower ranges, and consequently a point is eventually reached where the ultimate improvement ceases because the quality of the steam going into the exhaust represents a greater loss than the saving due to the reduction in internal friction.

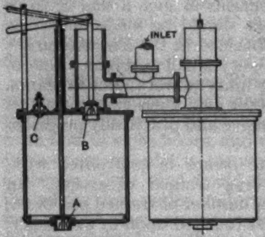

FIG. 5.—Weighing tanks

The authors rather broadly discount any value which may be given the indirect measurement; that is, appropriating the condenser as a large calorimeter. I have one test in mind particularly, where this method had to be resorted to, and by executing the work with every possible degree of precision, it served the occasion admirably. There were several different interests concerned, and efforts were combined to ensure reasonably close results. The Venturi meter installed was accurately calibrated over the range required by discharging into rectangular tanks which were accessible for the purpose. The meter coefficient determined by the builders was completely verified. To avoid liability of error in observing temperature of the discharge water, two calibrated laboratory thermometers were placed at virtually opposite points of the pipe and simultaneously read. Any variation throughout the body of water due to stratifying of the temperature, would have been noticed. These thermometers agreed as they were placed at the foot of a barometric tube which allowed time enough for the temperature to become evenly diffused. Furthermore, a recording thermometer was moved back and forth across the hot well discharge. The entire results were well within 1½ per cent correct.

In surface condenser work weighing tanks and standard scales are the rule in official testing. At some plants large weighing scales may not be readily obtainable, and arrangements of tanks shown similar to those in Fig. 5 has been used with success. A snifting valve is provided at "C" allowing the ingress and egress of air to and from the tank and which automatically closes when the tank is full, furnishing one signal to the operator to shift the levers. This, of course, represents only one of the tank arrangements that has proved a successful expedient.

Wm. C. L. Eglin: There are two phases of this discussion tonight, namely, the acceptance test and the manufacturers test. I hold some difference of opinion from the views expressed in the early part of the evening regarding the acceptance test. I do not believe the acceptance test is of any value unless it is made in the manufacturer's plant. I think Mr. Hodgkinson brought that out when he said the agreement was between the purchaser's engineers and the manufacturers' engineers.

It is very difficult to make corrections in such a way as to be satisfactory to both sides; so a test should be made under the conditions which can be reliably obtained in the manufacturer's plant; and that limits the test to very small turbines. One of the greatest difficulties is obtaining unity power factor in plants. When the turbine gets above 10,000 kw., then running a test under full rated load becomes expensive and practically precludes that class of testing.

There is another difficulty the owner is confronted with, and that is the difficulty of having trained observers. In the manufacturing plant there are a number of trained observers, and that is an advantage that is not touched upon in this paper.

This paper seems to indicate that the most necessary thing is to have reliable instruments. In a large equipment it would be almost impracticable to install additional instruments to the extent indicated by this paper; and from our standpoint, we would turn over the instruments and have them checked in place before the test was made. We have found that accurate results could be obtained from the steam flow meter and it is of great value in checking the operation.

For several reasons turbines have fallen off in efficiency, and by the use of the steam flow meter, we can determine that within a day or two of the changes in conditions.

The paper covers practically all the standard conditions of making a test; but from our standpoint we prefer a test covering a large period of time—of several days or a month—with our instruments checked by the regular operating force.

C. O. Mailloux: I have designed plants where turbines have been used. I want to emphasize the point made by Mr. Dunn in regard to the advisability of segregation tests. I have had at least two experiences which indicated the desirability of it.

In 1906 I was a member of an expert Commission, consisting of three men, sent to Europe, for the purpose of making a general investigation of the entire subject of steam turbines and turbo-generators. In the course of our peregrinations through the various countries of Europe and through the various shops where turbines were made—that is, at least so far as we were admitted into them—we found a remarkable diversity of opinion as to the relative merits of the turbo and the dynamo part. It made a great deal of difference as to whether we were speaking to the designer of the turbine or the designer of the dynamo. If we were speaking to the man who designed the turbine, the dynamo was blamed for all the trouble; and if we were speaking to the man who designed the dynamo, the turbine was blamed for all the trouble. The other instance where it was desirable to separate the losses in the turbine and the dynamo, was a case where I purchased a turbine in Europe to be used in this country by a client. The turbine was bought, subject to tests in Europe; and when it came here we repeated the tests. We found a wonderful discrepancy. It was hard to believe that the machine could have deteriorated so much in merely coming across the ocean. Yet it was difficult to put our finger on the leak, owing to the difficulty of making a test of such part of the machine by itself.

I agree with Professor Robb in regard to the length of time necessary to make a test after steady conditions have been obtained. I have oft-times taken the results of a test running from four to eight hours, and cut it into portions of one, two and three hours, in order to see whether the result as calculated from a portion of the time would differ from the result calculated for the whole time under uniform conditions; and I think, as Professor Robb does, that a period of one hour under steady conditions might be sufficient, particularly if you have proper means, as with a flow meter that is not open to various errors, and with them I think we could make tests in shorter time. In other words, we could make them by comparing instruments—input and output.

A. Henry Pikler: The authors in their paper say: "The use of watt-hour meters for this class of testing should be avoided wherever possible."

The adoption of such a principle I am afraid would introduce grave errors in the results. The efficiency test of a turbo-generator unit is a duration test, therefore the time-integral of the output should be measured and not the rate of output. This is especially important because, as known from experience, no matter how careful arrangements are made, the load will fluctuate. It is true that the watt-hour meter is not as accurate an instrument as an indicating wattmeter, yet its error can be ascertained accurately. Furthermore, the errors due to fluctuations in the load are far greater than the error in the watt-hour meter. Both instruments, the indicating watt-meter and the watt-hour meter should be in the circuit simultaneously, the indicating instrument serving as a check on the integrating instrument under the conditions given.

E. W. Yearsley: The steam flow meter is such a convenient means of measuring steam consumption, that it is important to know its approximate accuracy under various conditions. This paper refers to these meters in a general way. I should like to hear further expressions of experience regarding suitable circumstances and necessary precautions in the use of such meters. Within what percentage are they correct for measuring turbine consumption? Are they satisfactory if connected in a turbine branch, which is taken from a main steam line carrying reciprocating units in the immediate vicinity? How are they affected by the varying pressure of an exhaust steam line in a mixed flow turbine? Is it necessary to calibrate such meters when used to measure reciprocating engine consumption? What is the comparative accuracy of the Venturi and nozzle plug types for continuous and intermittent flow? Are the recording meters as accurate as the indicating meters? Do these meters retain their accuracy after operating for some time subject to considerable vibration?

E. B. Rosa: I have had no experience in testing turbo-generators, but we have had some experience at the Bureau of Standards in testing the instruments used in the electrical measurements made in such tests. We are very much pleased with the instruments that are being furnished by the best manufacturers for such purposes. If they are properly tested and calibrated, they are frequently more accurate and reliable than one would anticipate. Particularly is that true of potential transformers and current transformers. If they are properly calibrated, they are very reliable, and are indeed instruments of precision. The transformers are, perhaps, more reliable than the instruments used in connection with them, but the instruments used in connection with them may be trusted to give very good results, indeed.

If the results of a test are to be reliable to 2 per cent, each one of the many separate errors must be kept as small as possible, and that makes it necessary to use accurate and reliable instruments.

I did not see the paper before this evening, and have had no opportunity to read it carefully. I heard the greater portion of it read, however, and I must commend the discussion which is given in it of the electrical measurements to be made in such tests.

I would particularly like to speak about the shunts. There are more errors in shunts than many people using them imagine. I have known of instruments and shunts being sent for careful standardization after tests were over, whereas if they had been tested before they would not have been used. They should be tested both before and after, as Professor Robb has said. But if they are tested only once, it is rather better before the efficiency test than after, as it gives one opportunity to know their conditions and to discard unsuitable instruments.

The distribution of the current in the shunt is important, and the heating of the shunt is also important. If they are to remain in circuit during the run, carrying heavy load, they become heated, and obviously the effect of such heating should be definitely known.

L. T. Robinson: There are a few things I would like to refer to. The principal point in writing about measuring the electrical output was to emphasize the advantage of relying upon indicating instruments rather than watt-hour meters, when the most accurate results are demanded. Referring to some remarks that Mr. Hodgkinson made, I think he seemed to feel that the listing of so many precautions was rather a reflection on the intelligence of engineers in general but I would say that considerable experience with what actually does happen makes more careful attention to details desirable in many cases.

It has been my experience that tests are either left to a steam engineer or to an electrical engineer, and in some cases "the other end" suffers. That is, if he is a good steam engineer he gets the steam end all right and takes whatever is handy, and makes the electrical test with it.

With reference to Professor Robb's remarks, I think that the endorsement of the instrument transformers given by Dr. Rosa needs no further comment from me.

With reference to the provision for inserting portable standards for tests in connection with switchboard, instruments and meters I feel that this is something which will be brought about sooner or later. It would be very desirable to have such arrangements.

With reference to Mr. Dreyfus' remarks, I think any difference of opinion that might be apparent are due more to misunderstanding than anything else.

I did not intend to bring out—and I don't think Mr. Dickinson did—that accurate testing is something which can not be done, but rather that it is something which is being done right along; and the agreement obtainable between different test runs is about the same as that which he refers to.

With reference to meters correct within two per cent of accuracy—the Public Service Commission requirements, the whole paper is based on 2 per cent not being good enough.

With reference to Mr. Pickler's remarks about using the watt-hour meters, it is simply a misunderstanding. I have no objection to the use of the watt-hour meter if calibrated in place, and therefore corrected for all the errors that might influence it in use. But it is not in the same class as the portable indicating instruments, one being about five times as accurate as the other, to express it in terms of percentage.

I. E. Moultrop (by letter): Messrs. Dickinson and Robinson have very clearly outlined the essential features of commercial testing of steam turbo-generators. There is nothing in the paper which is new to the engineers of large power plants who have had to do considerable testing of this kind, still I think the authors might have placed more emphasis on a number of their recommendations.

The absolute tightness of a surface condenser is important and very difficult to determine when fresh circulating water is used. Also when the condensed steam is weighed, the temperature of the water should be taken. When the water rate of the turbine has to be determined by weighing the boiler feed the possibility of error is great and much care must be taken to eliminate such errors.

It is not easy to accurately measure the vacuum; the mercury column should be carefully checked and if possible the mercury should be boiled out before the test. All thermometers should have the same stem exposure as that under which they were tested.

I am surprised to see the steam flow meter so highly endorsed and wonder if its advocates would accept a test which showed by a steam flow meter only that the turbine failed to meet the contract guarantees.

The authors in their conclusion could well have emphasized the importance of insuring the accuracy of the electrical measurements, for I believe the liability of error in commercial testing is greater in this respect than in any other. I wish to endorse the recommendation that for commercial purposes a turbo-generator should be only tested as a combined unit and under the same adjustment it will have in regular station operation.

A very good check on a test of this kind is to work up the readings and plot the results as the test progresses, as many errors of observation become apparent at once and can either be corrected or the test can at once be repeated.

I think a little consideration of their paper will indicate that there are many power users who would find it difficult to make a satisfactory and reliable test on a new steam turbo-generator either on account of their operating conditions or by reason of the expense involved. As the manufacturers usually run the machine under steam before making shipment it should cost but little more to find a way to load the generator and make a complete test on the machine before shipment. If this were done correction could be eliminated because the steam pressure and temperature, the amount of vacuum, etc., could be made to agree with the terms of the contract. The load could be held steady and at unity power factor and a trained testing force employed which would add to the reliability of the results. I wish, therefore, to endorse the recommendation of Mr. Eglin that manufacturers should be prepared to make acceptance tests at their factory if requested by the purchasers.

In a plant of considerable size I believe there should be permanent testing facilities and periodic tests should be made on all prime movers. Steam turbines are much less liable to fall off in economy than engines yet things do occur which will seriously affect their efficiency.

The Edison Electric Illuminating Co. of Boston has such an equipment in its L. St. Station. It consists of a pair of large steel tanks each set on a platform scale in a room adjacent to the turbine room. A pipe line runs from these tanks to the condensed steam discharge of each turbine so that the manipulation of a few valves will divert the condensed steam from any turbine into these tanks. In the switchhouse a cell is equipped with special instrument transformers and arranged so that carefully calibrated test instruments can be readily installed in series with the regular switchboard instruments. By this arrangement a very good routine test can be made by the operating department at any desired time without interfering with the operation of the station, and at a slight expense.

E. D. Dickinson: It seems to me that the chief point of discussion this evening, with regard to this paper was the segregating of the turbine from the generator, and the remarks of Mr. Hodgkinson covered this rather completely. That is, if turbines are to be built and sold by themselves, the most accurate and positive method of testing is to build some device to measure the output of the machine to the satisfaction of every body, before it leaves the factory. Where turbines are built and sold with generators, it is the over-all efficiency of the unit that is of interest.

There were several questions asked, relative to the reliability of the flow meter after it had been in service some time. If I remember correctly, the gist of all was; is it an accurate device which can be put in the circuit and left there for a long period? We have had some of them, that were little more than laboratory meters, in service a long time, and they are as accurate now as when put in. Inaccurate indications will sometimes be caused by the holes in the nozzles getting clogged, but these are easily cleared.

Perhaps I did not understand Professor Robb in his remark about the use of valves for disconnecting certain sets of boilers, in order to make tests by weighing the water fed to those supplying steam for the turbine under test. We have heard of cases where valves separating different boilers and thought to be tight, were found after the tests were completed, not tight. The results were therefore valueless and the money spent had been wasted.

I wish to call particular attention to the communication from Mr. Moultrop in which he shows that accurate tests may be made in power stations, and at comparatively small expense.

The importance of being able to know at any time, the efficiency of apparatus in service should be sufficient to bring about a more general adoption of similar methods.

A paper presented at the Toronto Section of the American Institute of Electrical Engineers, Toronto, Can., November 19, 1909.

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TUNGSTEN LAMPS

BY G. S. MERRILL

The perfection of the tungsten incandescent lamp as a highly efficient means of converting electrical energy into light has made it a subject of great commercial interest. The tungsten lamp has reached in a comparatively short time a most enviable position in the field of artificial illuminants. It has been developed for multiple use on commercial lighting circuits up to 250 volts, for series street lighting, for low voltage decorative, display and train lighting, and for many other purposes. Its commercial success in all these various applications bears witness to its merit as a convenient and efficient source of illumination and its production and characteristics are consequently worthy of consideration from an engineering standpoint.

A discussion of the historical side of the high-efficiency lamp development is very interesting, but as this can be found fully covered in current technical papers it perhaps is not necessary to review the line of experimental and research work which produced the modern high efficiency lamp. Neither is it necessary to describe the several different processes by which various experimenters have produced tungsten filament, since these too can be found thoroughly covered in connection with the historical development.

The process most widely used in the United States to-day is one which starts with the purest tungstic acid or anhydride obtainable as its basic material. Tungstic acid is obtained commercially from the ores wolfram, a ferrous manganous tungstate, scheelite, a calcium tungstate, and hubnerite, an oxide of tungsten and manganese. The tungstic acid as received by the lamp manufacturer is in the form of a heavy yellow colored powder and notwithstanding its purity has to undergo a most thorough further purification and special treatment in order to reduce it to a fine yellowish powder which possesses a slight porosity. This peculiar physical condition is necessary for the successful reduction of the oxide, which can be accomplished in several different ways perhaps most easily by heating to redness in a current of hydrogen. Tungsten as used in steel making is reduced from the oxide by heating with carbon in crucibles, but the resulting metal is not pure enough for the manufacture of tungsten filaments, which are seriously affected by the presence of combined carbon. It is also possible to reduce the oxide by heating with metallic zinc, the two substances being in a finely divided state and thoroughly mixed before heating.

The tungsten as obtained from the process of reduction employed in lamp manufacture retains the physical characteristics of the oxide inasmuch as it is finely divided and slightly spongy. The metal in a mass has a bright metallic luster resembling platinum. In the powdered state it is grayish black or dead black depending upon the fineness of the powder and the temperature of reduction.

After obtaining this very pure metallic tungsten, the next operation is to mix it with a binding material in order to form a plastic mass that may be squirted into the fine threadlike filaments. Various substances can be used for this purpose but some compound of carbon, oxygen, and hydrogen such as starch, sugar, camphor, etc., is usually employed. The metallic powder when mixed with such a binding material has somewhat the consistency and appearance of black putty. It is absolutely smooth and uniform and it is impossible to detect the slightest grain. This paste, as it is called, is placed in a small steel cylinder and forced, by a pressure of about 32,000 lb. per sq. in., through a small diamond die.

The die used in squirting tungsten filament consists of a suitably mounted diamond of from one-half to one carat in weight through which a very minute hole has been drilled. In the smaller dies used to-day this hole is only about 0.0014 in. in diameter which is smaller than an ordinary hair. The hole is drilled in the diamond with a steel needle, ground down so fine that it is as flexible as a hair and, as can be imagined, the drilling requires considerable time and patience. The stone when drilled is mounted in a steel casting in order to hold it against the enormous pressure used in squirting the filament.

Under such pressure the abrasion of the die even by the smooth tungsten paste is very rapid. This abrasion is a serious matter as the diameter of the hole, and consequently that of the filament squirted, constantly increases. Moreover the abrasion is not uniform, so that the hole enlarges more rapidly in the direction of one diameter than of the other, assuming when worn an elliptical shape. After enough filament for about 1,500 lamps has been squirted, it is necessary to have the die rebored, an operation which costs almost as much as the original die. A die cannot be rebored more than twice before it develops cracks or fissures which cause it to break. The next hardest material, sapphire, has been experimented with as a material for these dies but it is found that such a die is very liable to split and that it will hardly make 100 lamps before it needs re-drilling.

The filament, after squirting, has been likened in character to a filament of putty, that is, while holding its form well and being flexible to some extent, it is liable to break if bent sharply. The filament as squirted is looped back and forth on cards and after being allowed to dry is cut to form a number of single loops much as they are seen in the finished lamp.

The next operation is to heat the filaments in an inert gas, or in one chosen to act upon the particular binding material employed, until they reach a red heat which removes any moisture and lighter hydrocarbons that may be present. Each filament is then mounted in current conducting clips so that it may be heated by passing an electric current through it. During this final heating or forming, as it is termed, the filament is supported vertically with the loop downward. A very small weight (a few milligrams) is hung in the loop to prevent the filament from being distorted in shape during the heating which is usually performed in either an inert gas or in a very good vacuum, the gas, if used, being again dependent to some extent on the binding material employed. The temperature of the filament is raised gradually, allowing time for the proper reactions and physical changes to take place. During the heating, the energy input into the filament rises to about fifteen times that finally required in the lamp, and while some heat is carried away by the forming gas the temperature is undoubtedly much higher than that reached in subsequent operation.

Every trace of binding material is driven out, and the filament when finally brought to a sufficiently high temperature undergoes a sudden and marked contraction in diameter and length as the small semi-molten particles become soft enough to merge into one perfectly homogenious mass. A piece of such filament under a microscope resembles a drawn wire and while the surface is not perfectly smooth there is no indication of a granular structure.

At a dull red heat any good tungsten filament is flexible enough to be bent as desired but when cold is somewhat fragile. For this reason it is a good thing if possible to light tungsten lamps while cleaning them, the chance of mechanical breakage being then minimized. Lamp packages have been devised that eliminate a considerable amount of breakage that would result from rough handling so that, if the lamps are left in the original cartons until placed in service, and handled with even ordinary care, the question of breakage will be found to be of little importance.

In order to secure a uniform quality of filament, which is absolutely necessary for good lamp making, every step of the entire process of production even to the smallest detail must be carried through with exactness. For example the rate at which the temperature of the filament is raised during the forming process has a most important effect on the final filament structure, and must be carried out with extreme care in order to assure a perfectly uniform run of filament.

After forming, the filaments are mounted upon the familiar glass supporting rod as seen in the finished lamp, and the joint between each leg and the supporting and conducting terminal made by electrically welding the filament to the support. This makes a very perfect joint both electrically and mechanically.

The material used for the hooks and supporting wires affects the performance of the lamp to a considerable extent. Soft copper is used extensively for such supports, also, to a somewhat lesser extent, molybdenum, tungsten, tantalum, thoria, carbon, platinum, iridium, or other refractory materials. Soft copper does not alloy with pure tungsten and moreover occludes but very little gas so that it makes a very satisfactory form of supporting hook.

The process of producing a high vacuum within the bulb of a tungsten lamp is a great deal more laborious than in case of the carbon lamp. It is necessary, in order to produce a good lamp, and this applies to carbon and other types as well, to remove every trace of gas, not only that actually free at the time of pumping but that which may later be liberated from anything within the finished bulb. A good lamp vacuum is only possible through the use of very perfect exhausting machinery and through subjecting the entire lamp, filament, glass, and other parts to a proper heat treatment, during the pumping process. The heat treatment tends to drive from the glass walls and other surfaces exposed within the bulb the particles of air which cling to them in a thin film with surprising persistence. A glass bulb pumped while cold will apparently reach a high degree of exhaustion at the end of the pumping process, but, if left standing for some time, will be found to possess a very poor vacuum as judged from that required to insure good lamp performance. This is due to the gradual liberation of particles of air which, during the pumping, cling to the interior surfaces. The filament is heated intensely by passing an electric current through it while on the pump in order to drive from it and from the supporting wires, which are heated by the incandescences of the filament, any occluded gas which may later be freed from these parts and thus spoil to a certain extent the perfect vacuum required for successful operation. During the pumping process the filament temperature must be regulated with great care, the temperature being raised gradually as the bulb becomes evacuated. If, for example, the temperature should be raised, too quickly, a thin film of oxide will form on the surface of the filament which, although entirely removed by a further rise in temperature and higher degree of exhaustion, will have been found to have caused a slight change in the character of the surface of the filament, altering thereby its emissivity and radiating properties and injuring its subsequent life performance.

After pumping, the lamps are given an exhaust inspection and aging by burning at a certain percentage over voltage. If during this inspection any lamp develops or shows a bluish color or haziness within the bulb it is an indication of imperfect vacuum and the lamp is rejected. The period of burning and per cent over voltage depends somewhat on the size of the lamp, but in every case has been chosen so that if a lamp is at all likely to develop a poor vacuum it will be disclosed on this inspection.

The glass work required in making the tungsten lamp is, with the exception of the center glass stem, practically the same as in the other types of incandescent lamps.

I have now covered in a general way the process of producing the tungsten lamps, and have I hope given some slight idea as to the care required in such production. In order to show the performance of the lamps in subsequent service, I have averaged the candle-power life curves of 50 40-watt tungsten lamps which were burned on life test at constant voltage corresponding to an initial consumption of 1.25 watts per mean horizontal candle-power. The curves in Fig. 1 show the change in candle-power, current and efficiency during the period of test, which was stopped at about 1,400 hours. In order to show the life performance, a curve is given showing the per cent of lamps which were burning at the end of various periods of time. These curves, Fig. 2, are the average obtained from 80 40-watt tungsten lamps burned under same conditions as the previous

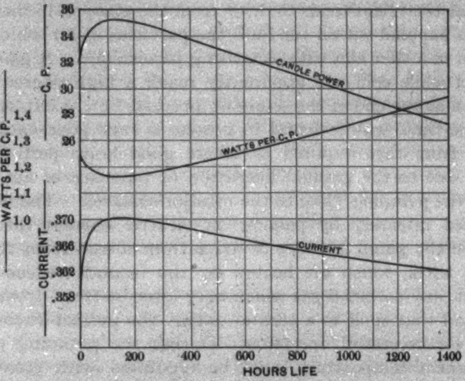

FIG. 1.—Characteristic performance of 40-watt tungsten lamps

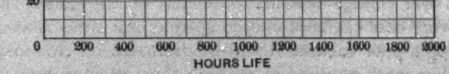

FIG. 2.—Mortality curve of 40-watt tungsten lamps

FIG. 3.—Unmounted tungsten filament

FIG. 4.—25-watt tungsten—400 hr.—alternating current

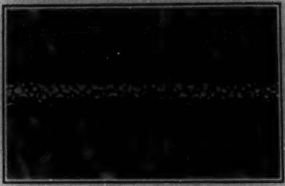

FIG. 5.—40-watt tungsten—180 hr. —alternating current

FIG. 6.—25-watt tungsten—1400 hr.—alternating current

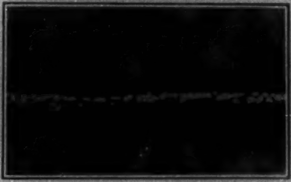

FIG. 7.—40-watt tungsten—898 hr.—alternating current

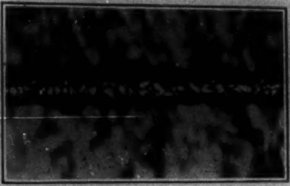

FIG. 8.—40-watt tungsten 2190 hr.—alternating current

FIG. 9.—40-watt tungsten—300 hr.—direct current

FIG. 10.—40-watt tungsten—3000 hr.—direct current

FIG. 11.—100-watt tungsten—1400 hr.—alternating current

FIG. 12.—250-watt tungsten—2000 hr.—alternating current

FIG. 13.—Tungsten—Street series 2000 hr.

FIG. 14.—Tungsten—street series—3349 hr.

FIG. 15.—80-watt tantalum—50 hr.—alternating current

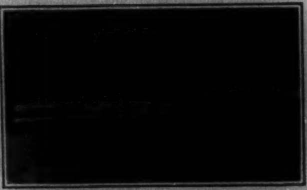

FIG. 16.—80-watt tantalum—400 hr.—alternating current

FIG. 17.—40-watt tantalum—800 hr.—alternating current

FIG. 18.—80-watt tantalum—948 hr.—alternating current

FIG. 19.—80-watt tantalum—60 hr.—direct current

FIG. 20.—80-watt tantalum—455 hr.—direct current

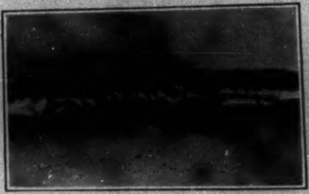

FIG. 21.—80-watt tantalum—1058 hr.—direct current

FIG. 22.—Gem—841 hr.

FIG. 23.—Carbon—508 hr.

test *i.e.*, at 1.25 watts per c.p. About one half of the lamps were burned in a horizontal position and the others in a vertical position, tip downward. These tests were stopped at the end of 2,000 hours.

The change in appearance of the filament during life is rather interesting, and some illustrations showing filaments taken from lamps which had burned for various lengths of time are shown in Figs. 3 to 23. For comparison, a few tantalum filaments as well as filaments from a gem and from a carbon lamp are shown.

The relation between candle-power watts, amperes, ohms, volts and watts per candle is shown by the characteristic curves of tungsten, Fig. 24.

For the normal range of operation these curves can be expressed in the form of parabolic equations a few of which are as follows:

Let C = candle-power.
e = efficiency in watts per candle.
V = voltage.
W = total watts.

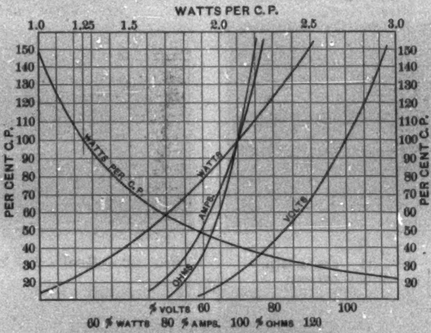

Fig. 24.—Performance of tungsten filament lamp

then

$$\frac{C_1}{C_2} = \left(\frac{e_2}{e_1}\right)^a$$

$$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^b$$

$$\frac{W_1}{W_2} = \left(\frac{V_1}{V_2}\right)^d$$

APPROXIMATE VALUES OF EXPONENTS

	a	*b*	*d*
Carbon	1.58	5.55	2.05
Gem	1.57	4.80	1.75
Tantalum	1.67	4.35	1.74
Tungsten	1.75	3.68	1.59

Values of the exponents are given not only for tungsten but for carbon, gem and tantalum as well, for purpose of comparison.

A series of values showing relation between voltage and candle-power variation for the four types of lamps has been calculated, and shows the great advantage which the metallic filament lamps, particularly the tungsten, possess over the carbon lamp.

Per cent change in voltage		Per cent change in candle-power			
		Carbon	Gem	Tantalum	Tungsten
Increase above normal	10	69.8	58.0	51.4	42.1
	9	61.4	51.3	45.5	37.4
	8	53.4	44.7	39.8	32.8
	7	45.6	38.4	34.2	28.3
	6	38.2	32.3	28.9	23.9
	5	31.1	26.4	23.6	19.7
	4	24.3	20.7	18.6	15.5
	3	17.9	15.2	13.7	11.5
	2	11.6	10.0	9.0	7.6
	1	5.7	4.9	4.4	3.7
Normal............		0	0	0	0
Decrease below normal	1	5.4	4.7	4.3	3.7
	2	10.6	9.3	8.4	7.2
	3	15.5	13.6	12.4	10.6
	4	20.3	17.8	16.2	13.9
	5	24.8	21.8	20.0	17.2
	6	29.0	25.7	23.6	20.4
	7	33.2	29.4	27.1	23.4
	8	37.1	33.0	30.5	26.4
	9	40.7	36.4	33.6	29.3
	10	44.3	39.7	36.8	32.2

An increase of 6 per cent in the voltage of a carbon lamp increases the per cent candle-power as much as an increase of 9 per cent in voltage of the tungsten lamp. While a tungsten lamp 10 per cent under voltage drops in per cent candle-power only as much as a carbon lamp 7 per cent below normal. For a circuit where the regulation is poor, the tungsten lamp will be found to give much better satisfaction as far as variation in candle-power is concerned than the carbon lamp.

The size and length of filament required in lamps of various candle-powers and voltages varies considerably. For 110 volts the size and length varies from a diameter of 0.0013 in. and a total length of 17.4 in. for a 25-watt lamp to a diameter of 0.0060 in. and a total length of 37.56 in. for a 250-watt lamp.

The specific resistance of tungsten is about 46.5 ohms per mil-inch at a temperature corresponding to 1.25 watts per c.p. and about 9 per cent of this figure, or 4.19 ohms per mil-inch, at ordinary room temperature. This low cold resistance has led to a good deal of discussion as to the value of the starting current obtained upon closing the circuit of a tungsten lamp and its effect upon the filament.

The question is of particular importance when the lamps are turned on and off continuously, as for example in flashing sign work. We have obtained experimentally the cooling curves of several sizes of tungsten lamps, which are shown herewith, plotted as resistance against time, Fig. 25. As would be expected, the larger lamps cool much more slowly than the smaller ones, as shown by the drop in resistance. It takes the 250-watt lamp, burning at 1.25 watts per c.p., 58 seconds after being turned off, to fall to 200 per cent of its initial cold resistance, while it takes the 60-watt lamp only 20 seconds, the 25-watt lamp about 11 seconds and the small low voltage sign lamp a little over six seconds. The filament of the latter lamp is actually heavier than that of the 25-watt lamp, but, being much shorter, cools more rapidly by conduction of heat by the terminals and anchor.

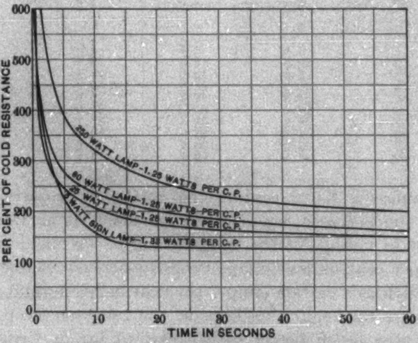

Fig. 25.—Cooling curves of tungsten lamps

In ordinary flashing sign work, four seconds can be assumed as an average period of flashing; this would allow the sign lamp to drop to only 250 per cent of its cold resistance between flashes, or the ratio of hot and cooling resistance when flashed in this way would be about one to four. This would act to greatly reduce the over-shooting effect.

From tests conducted on a few lamps flashed at various intervals, it is so far believed that flashing will have no injurious effect on the lamps in regard to life performance.

Having now covered the general method of manufacturing the tungsten lamp and a few of its characteristics we may turn our attention to the reason of its high efficiency.

A body at any temperature other than absolute zero will radiate energy in all wave lengths from zero to infinity, having a maximum radiation at a wave length which varies with the temperature. At low temperatures the actual amount of energy radiated is very small, and beyond narrow limits on either side of the maximum is infinitesimal.

The general distribution of energy so radiated is shown by the curves in Fig. 26. The total amount of energy radiated in a given time is represented by the total area under the curve and has been found to increase as the difference of the fourth powers of the temperature of the radiating body and the temperature of its surroundings. Not only does the actual rate of energy radiation vary as a function of the temperature, but the manner in which the energy is radiated also changes. This change takes place as shown by the shift in the maximum point of the curves plotted for the radiation of a body at different temperatures. The radiation from most bodies follows a very complex law and has been thoroughly investigated only for a complete radiator or theoretical black body, which is represented in the curves shown. The same general law holds for other bodies as well as the theoretical black body considered.

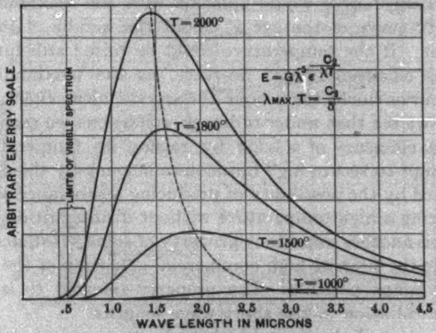

Fig. 26.—Black body radiation

Referring to the energy-wave length curves the area under the curves represents the total energy radiated by the body at the several temperatures. The visible spectrum which includes only the wave lengths capable of exciting the retina of the eye represents but a small portion of the total range of radiation and the energy radiated in the visible spectrum represents a still smaller portion of the total amount of energy radiated. The ratio of the energy radiated in the visible spectrum to the total energy radiated is an indication of the luminous efficiency and since the maximum point of the energy curve shifts toward the visible spectrum, as the temperature rises, as shown by the dotted line, the luminous efficiency increases with the temperature.

It we could secure a black body capable of operating at extremely high temperatures and a means of producing such temperature we would find a limit to our efficiency of light production at about 5000 deg. absolute at which point the maximum of the energy curve would coincide with the maximum of the sensibility curve of the eye at about the middle of the visible spectrum. If the temperature could be raised still further the luminous efficiency would decrease, as the maximum of the energy curve would then move toward the ultra violet. Consequently we see that under ordinary conditions we can raise the luminous efficiency of a body by raising its temperature. In the attempt to secure high luminous efficiency by this means we are limited by the possibility of producing a substance capable of maintaining a high temperature without disintegration.

There is another important property of some substances which has made the present high commercial efficiency of the metallic filament lamps possible. The property referred to is that of selective radiation in the short wave lengths.

We have used the term black body or complete radiator to describe a body which will radiate at any temperature a maximum amount of energy in every wave length. Such a body would also be a complete absorber and would therefore absorb all energy incident upon it. A body, which is not a complete radiator, will at a given temperature radiate less energy in each wave length than a black body at the same temperature. If the energy radiated in each wave length is reduced by a constant proportion, the ratio of energy radiated in the visible spectrum to the total energy radiated will be the same as that of a black body, and the luminous efficiency would be the same as that of a black body at the same temperature. Such a body is termed a gray body, and in place of absorbing all energy, which falls upon it, it would reflect a constant percentage of each wave length.

If a body not only radiates less energy than a black body at the same temperature, but in addition radiates a relatively larger proportion in one part of the spectrum than in another, compared to the black body it may be said to radiate selectively in that part of the spectrum. If the body radiates selectively in the short wave lengths the luminous efficiency will be higher than that of a black body at the same temperature. We would expect to find in the case of such a body that the absorption of energy would not be the same for different wave lengths but that the body would absorb a greater proportion of those wave lengths which it would radiate selectively when heated. A comparison of the reflecting power at different wave lengths for different substances is very interesting in showing how it is possible to gain in efficiency of light production by employing materials capable of selective radiation. Fig. 27 shows the percentage of energy of various wave lengths reflected from several different substances. A black body would have zero reflecting power throughout, a gray body a constant per cent throughout while a body capable of selective radiation a varying per cent. All the metals shown here have a tendency to reflect less energy in the visible spectrum than in the infra red, where the reflecting power rises to a very high value. Consequently since they absorb relatively more energy of the visible spectrum, they would, when heated, tend to radiate relatively more energy in the same part of the spectrum, and would therefore be found

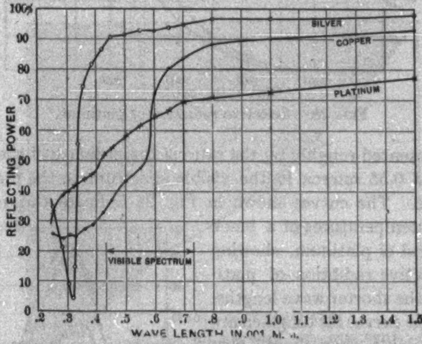

FIG. 27.—Percentage of energy of different wave lengths reflected from silver, copper and platinum*

to be more efficient luminous radiators than a black body at the same temperature. The relative percentage of energy in the visible spectrum to total energy at different temperatures can be represented roughly by the ratio of the ordinate of the energy curve at 0.55 micron in the visible spectrum to the maximum ordinate. The curves shown in Fig. 28 indicate this ratio for various temperatures of a black body, and of platinum, showing the selective radiation of platinum in the shorter wave lengths. While the curves for tungsten are not available they should possess the same general characteristics as the metals shown.

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*Data from Landolt-Börnstein, Physikalisch-Chemische Tabellen.

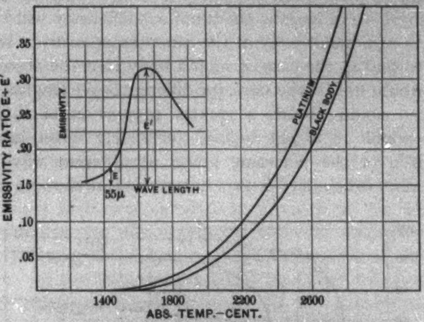

Fig. 28.—Selective radiation of platinum

Another way of showing the selective radiation is by means of actual energy curves taken through the range of principal radiation. Fig. 29 shows a series of curves determined by the Bureau of Standards showing the energy distribution of various filament materials when operated so that the light distribution is practically the same throughout the visible spectrum. It can

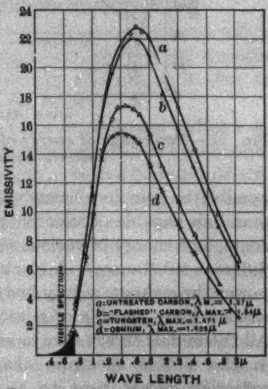

Fig. 29.—Curves of energy distribution of filament materials*

be shown that the temperature of the tungsten filament in this comparison is at least as low as that of the carbon filament so that, under actual working conditions, the difference between the energy curves would be still more striking since a further gain in luminous efficiency is made possible by the higher normal operating temperature of the tungsten filament.

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*Coblentz, "Radiation Constants of Metals"; Bulletin of the Bureau of Standards, Vol. 5, No. 3.

High commercial efficiency of incandescent lamps cannot be expected to result from high temperature alone but from a combination of high temperature with a property of selective radiation. The possibility of operating a filament at a high temperature is a very good feature but the disintegration of the filament, which increases more and more rapidly as the temperature rises places an upper limit on the temperature at which it is possible to operate a filament and still obtain a commercial life, so that we cannot look to high temperature alone for a solution of the problem. The temperature at which it is possible to operate a filament, and secure a reasonably long life, depends not so much on the melting point as upon the ability to withstand surface evaporation in a high vacuum.

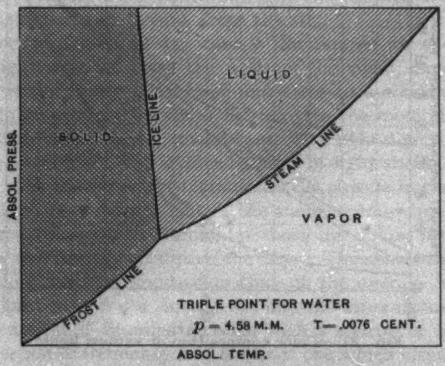

Fig. 30.—Pressure-temperature diagram

The conditions that exist in a lamp of high exhaustion in regard to melting and vaporization are rather interesting. If we plot a pressure temperature diagram for any substance we find that the three states of the substance will be represented by three areas bounded by three curves which we would call, in speaking of water, the steam line, the ice line and the frost line. See Fig. 30. The intersection of these three curves gives us the location of the " triple point ", or the pressure and temperature at which it would be possible to have the substance existing in these three states at the same time.

In an incandescent lamp bulb the pressure is exceedingly low, something of the order of 0.001 mm. of mercury, so that we may believe while not being able to prove conclusively that at normal operating temperatures of the filament we are working on a part of the diagram below the triple point, there would therefore be a tendency for the material to evaporate slowly from the filament surface, as it apparently does. That the temperature of commercial operation is not dependent upon the actual melting point may be shown by the rapid disintegration of a carbon filament if operated at the normal temperature of a tungsten filament in spite of the fact that the true melting point of carbon is probably higher than that of tungsten.

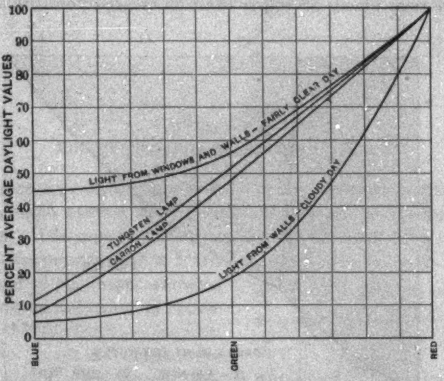

FIG. 31.—Color composition of various lights

The tungsten lamp is, because of its selective radiation and higher filament temperature, superior to the older types of incandescent lamps in the quality of its light. Under normal working conditions the tungsten favors the shorter wave lengths through the visible spectrum, giving relatively more blue radiation than the carbon lamp for an equal amount of red. The accompanying curves, Fig. 31, show the relative amounts of red, green, and blue in several types of lamps compared to daylight. The term, daylight, as ordinarily used is rather indefinite, as the proportion of red, green and blue in the light from a cloudy sky is different from that of a clear blue sky, which, again is different from that of direct sunlight. The comparison in this case is made to average outdoor daylight, as obtained from careful observation over a considerable length of time, and which is represented as 100 per cent red, 100 per cent blue and 100 per cent green.

I have drawn two other curves, which may be taken to represent the composition of light as it actually may exist in interior daylight illumination. Due to the reflection from surrounding objects, both without and within, it is usual to find the light in a room possesses a markedly different composition from the average light received directly from the sky.

An object in a room in day time is illuminated for the most part by light reflected from the walls of the room, except, of course, if it is directly in front of and close to a window. At night, with an artificial source of light within the room, the objects are illuminated for the greater part with light directly from the artificial source. The artificial source of light should therefore be of such character as to illuminate the objects in the room by its direct rays with a light of the same average quality or color value as that which illuminates them by diffuse reflection from walls and furnishings during the day. The nearer the color curve of an illuminant approaches that of the average interior light of a particular room during the day the more natural will the room appear if illuminated with such a source of light.

The question of frequency and flicker is one which often arises in connection with the use of the tungsten or other high-efficiency lamps on low-frequency power circuits. The candle-power of an incandescent body varies with the temperature. The temperature depends upon the relative rate at which energy is put into the filament and the rate at which it is dissipated by radiation, conduction and convection. When the energy is supplied at a changing rate, as by an alternating current, the temperature will fluctuate in synchronism with the power wave, or at double the frequency of the supplied e.m.f. The amount of variation in temperature during one cycle will depend upon the resistance temperature coefficient of the filament, its mass, diameter, specific heat, emissivity, and upon the wave shape and frequency of the energy supplied. If the frequency is low enough the temperature will fluctuate over wide limits. The amount of temperature fluctuation decreases greatly as the frequency increases, due to the thermal capacity of the filament. When the frequency of the electric circuit reaches about 25 to 27 cycles the flicker of most incandescent lamps giving usual intensities of illumination becomes imperceptible, although, it may in some cases be detected momentarily by rapidly moving the eyes from one object to another. The flicker effect at a given frequency will be more noticeable with a thin filament than with a heavier one of the same material since the quantity of heat contained at a given temperature varies as the mass or diameter squared, while the radiating surface varies only as the diameter to the first power.

In comparing tungsten and carbon filaments of the same diameter we must bear in mind that the higher specific heat of carbon tends to maintain its temperature more nearly constant with varying power input than in the case of the tungsten, while its higher emissivity tends to produce a more marked variation. Since, however, the diameter of a tungsten filament is less than that of a carbon filament for same voltage and candle-power, the carbon lamp is actually found to show a less tendency to produce visible flicker.

The question of flicker further involves the ability of the eye to detect a rapid variation in luminous intensity and it has been shown that the eye becomes less sensitive to the effect of flicker, as the average intensity of the illumination decreases. We have found, from experimental work, which is as yet not complete enough for more extended discussion, that the critical frequency at which it is possible to detect flicker varies as a function involving the product of the average intensity of illumination and the per cent variation in intensity. Thus the question as to whether a given lamp will show a flicker when operated at a certain frequency depends a great deal upon the average intensity of the illumination produced.

If we judge the flicker of a lamp at a certain low frequency by viewing a large surface illuminated by the lamp we would find that as the distance between the lamp and the surface increased the flicker would become less and less perceptible, diminishing with the intensity of illumination until, beyond a certain value of illumination no flicker could be detected. This characteristic of the eye enables comparatively low frequencies to be used successfully with low values of illumination.

The question of flicker is perhaps of most importance in connection with street series lighting, since, in ordinary multiple lighting, higher frequencies are usually employed. The street series tungsten should prove capable of successful operation at comparatively low frequencies for two reasons; first, the filament is heavy, which tends to reduce the variation in candle-power throughout a cycle; and second, the low value of illumination generally used in street lighting would tend to make any varaition in intensity of illumination less perceptible to the eye.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1910.

The Board of Directors of the American Institute of Electrical Engineers presents herewith for the information of the membership its annual report for the fiscal year ending April 30, 1910. The report shows the financial status of the Institute, and includes brief statements regarding the work accomplished by the various standing and special committees

The Annual Convention was held at Frontenac, New York, June 28-July 1, 1909. The total registered attendance was 252. Thirty-six professional papers, including the President's annual address were presented and discussed.

The Board of Directors has held 10 regular monthly meetings during the year.

A number of important changes in the policy of the Institute were effected during the year. Among these was the action resulting from the proposed formation of technical sections, the object of the movement being to broaden the work and scope of the Institute so as to cover as far as possible the entire field of electrical engineering. Upon recommendation of the Law Committee, to which the matter was referred, the Board of Directors at its meeting held on November 12, 1909, adopted resolutions authorizing the President to appoint additional special committees, to promote Institute activity in their respective fields, this being determined upon as the best means of meeting the situation.

On January 14, 1910, the Board adopted resolutions authorizing the holding of Institute meetings under the auspices of Sections. The object of these resolutions has already been clearly set forth in an article by President Stillwell printed in the April 1910 Proceedings. The resolutions were printed in full in the February Proceedings. In accordance with this action a successful Institute meeting was held in Boston, February 16, 1910. Other important resolutions adopted by the Board on January 14, 1910, related to the publication of informal communications in the Institute Proceedings. These resolutions were printed in full in the February 1910 issue.

Another important act of the Board during the year was to create wider distinction between the Institute Proceedings and Transactions. This was discussed at the meeting of the Board held on November 12, 1909, at which a resolution was adopted instructing the Meetings and Papers and Editing Committees to select from the Proceedings for publication in the Transactions only such papers and discussions as might be deemed worthy of permanent record and in making such selection no distinction is to be made between papers presented at the Annual Convention or monthly meetings of the Institute and those presented at any meeting of any Institute Section.

Closer relations between the Institute and the Sections and Branches have been established during the year by the action of the Board in authorizing the Secretary to make a tour of the Pacific Coast and arrange to meet as many western members as possible. This tour was most successful, as may be judged by the Secretary's report to President Stillwell, published in the November PROCEEDINGS. In carrying out this policy the Secretary during the year has visited meetings or conferred with groups of members at the following places, in most of which Sections and Branches existed or have since been organized: Seattle, Portland, Oregon; San Francisco; Los Angeles; Salt Lake City; St. Louis; Washington, D. C.; Boston, Mass.; Philadelphia; Urbana, Illinois; Chicago; Ames, Iowa; St Paul; Madison, Wisconsin; Milwaukee; Fort Wayne; Lewis Institute, Chicago; Armour Institute, Chicago; Charlotte, N. C.; and Pittsfield, Mass., involving a total of approximately 17,000 miles of distance travelled.

Sections Committee..—The Sections Committee is able to report very satisfactory progress in the work of the Sections and Branches during the past year, and a healthful state of affairs at the present time.

Two new Sections have been authorized during the year—one at Portland, Oregon, on May 18, 1909, and the other at Milwaukee, Wis., on February 11, 1910. The Milwaukee Section is undertaking an important development in Section work by coöperating with a local engineering society and local sections of other national engineering societies in such a manner that the efforts of all of these various engineering bodies shall be combined into a harmonious whole, so far as that particular locality is concerned.

Five new Branches have been organized during the year, as follows:

State University of Iowa, May 18, 1909.
Agricultural and Mechanical College of Texas, November 12, 1909.
Rensselaer Polytechnic Institute, Troy, N. Y., November 12, 1909.
Colorado State Agricultural College, February 11, 1910.
North Carolina College of Agriculture and Mechanic Arts, February 11, 1910.

The following table will serve to show the activities of the Sections and Branches for the past three years:

SECTIONS	For Year Ending May 1, 1908	May 1, 1909	May 1, 1910
Numbers of Sections	21	24	25
Section meetings held	141	160	187
Original papers presented	120	167	178
Attendance	7,476	16,427	16,694
BRANCHES			
Number of Branches	22	26	31
Branch meetings held	143	198	237
Original papers presented	84	158	147
Attendance	4,128	8,443	10,255

Meetings and Papers Committee.—The organization of the Meetings and Papers Committee has been materially changed during the past year by the appointment of the chairmen of the special technical committees to membership on the Meetings and Papers Committee and the enlargement of special committees. A further change has been made in holding the special technical committees responsible through their chairmen for Institute activity in the several branches of electrical science covered by them. It was also decided, early in the year, with the approval of the Board of Directors, to hold Institute meetings in different sections of the country, to encourage and develop interest and activity in the Institute work among the entire membership. The result of these changes in organization and methods has been a gratifying increased activity in the Institute work and the broadening of the scope and influence of the Institute.

During the past year this committee arranged for eight regular meetings, two largely attended special meetings, one at Charlotte and the other at San Francisco, the latter under the auspices of the High-Tension Transmission Committee. An adequate number of interesting papers were presented. These meetings partook of the general character of conventions. Two meetings were also held in coöperation with the American Society of Mechanical Engineers and two additional special meetings were held, one at New York and one at Boston.

Educational Committee.—The work of this committee for the year has consisted principally of arranging the April meeting of the Institute at New York, at which a paper on the subject of " Education for Leadership in Electrical Engineering " was presented by Dr. Samuel Sheldon.

The committee desires to emphasize the fact that the Institute has been more active in giving attention to educational matters than any of the other professional engineering organizations in the United States, and it is believed that this has been an important factor in the development of the Institute.

Electric Lighting Committee.—Regular monthly meetings of the committee have been held during the Institute year and the committee has arranged for the presentation of two papers on the subject of electric lighting at the May 17 meeting. Also, three papers have been obtained by the committee for presentation at the 1910 Convention.

High-Tension Transmission Committee.—An Institute meeting was held under the auspices of this committee on December 16, 1909. The committee also assisted in the Charlotte meeting and arranged for a Pacific Coast meeting of the Institute at San Francisco, California, May 5–7, 1910. Several valuable papers and much interesting discussion were obtained by the committee for presentation at these various meetings.

Industrial Power Committee.—Through the efforts of the committee practically all of the Sections and Branches have devoted one meeting this year to industrial power subjects. The March meeting of the Institute in New York was held under the auspices of the committee, as was also a joint meeting in Boston on February 16, 1910. A meeting was also held in New York on April 12, 1910, in coöperation with the American Society of Mechanical Engineers. An attempt is now being made to collect the papers on the subject presented before the various Sections, with the idea of publishing them in book form if feasible.

Railway Committee.—The Railway Committee has been active in obtaining papers in its field during the past year. Two Institute meetings, devoted to railway subjects, were held in New York under its auspices, and the committee has arranged for a special meeting to be held in New York on May 27, 1910. The committee has broken considerable new ground and will have several subjects to transmit to next year's committee through the Board of Directors. Among these is a suggestion for a change in policy in the manner of conducting a number of special meetings under the auspices of the Committee next year.

Telegraphy and Telephony Committee.—The meeting of the Institute at New York on February 11, 1910 was held under the auspices of this committee. A paper was presented dealing with modern automatic telephone apparatus.

Editing Committee.—Since May 1, 1909, there have been edited and published 12 numbers of the PROCEEDINGS. The total number of pages contained in these PROCEEDINGS is 2,262. Of this total, 402 pages have appeared in Section I, and 1,860 pages in Section II. Of the 1,860 pages in Section II, 1,257 pages were devoted to technical papers, and 556 pages to discussions. Volume XXVIII of the TRANSACTIONS, consisting of the papers and discussions during the calendar year 1909 and the report of the Board of Directors for the fiscal year ending April 30, 1909, contains 1,572 pages. Volume XXVIII will be issued in two parts. Part I, consisting of 752 pages, will contain the papers and discussions presented between January 1, 1909, and the session of June 29, 1909, at the Frontenac Convention. Part II, consisting of 820 pages, will contain the papers and discussions presented between the session of June 29, 1909 at the Frontenac Convention, and December 31, 1909; also the paper read by Mr. H. G. Stott before the Toronto Section on December 18, 1908.

From May 1, 1909 to April 30, 1910 there have been published in full in the PROCEEDINGS five papers read before various Sections and Branches, in addition to four abstracts of such papers, which appeared in Part I of the PROCEEDINGS.

The Editing Committee has gone carefully over the discussions which have been submitted by the Sections and Branches, and has also given its attention to the discussions presented at the New York meetings, to the end that much matter of temporary value has been eliminated and a higher standard of composition as well as material has been maintained. The committee has had under consideration the introduction of metric equivalents in the Institute publications, and has recommended to the Board of Directors that the suggestion of the Standards Committee relating to metric equivalents be given a trial should the Meetings and Papers Committee concur. The Editing Committee also has under consideration the publication of the material presented at joint meetings with other societies.

Standards Committee.—The Standards Committee has held five meetings in New York during the year. The committee has not undertaken a revision of the Standardization Rules this year, but has confined its work in that direction to preparing a separate list of recommended additions and amendments to the rules. This list is being prepared, and will be submitted at a later date.

The committee has had under consideration a revision of the Institute Copper Wire Table. Prior to undertaking this work, however, the committee consulted the Bureau of Standards concerning the most reliable and advantageous data to employ. The Bureau has taken these questions under consideration.

At its meeting held on December 16, 1909, the committee voted to recommend to the President and Board of Directors of the Institute the adoption of a by-law providing that metric equivalents shall be printed in parentheses after numerical expressions in English units in the Institute publications. This vote was communicated to the President on January 5, 1910, and the recommendation is now being jointly considered in conference between the Editing, and Meetings and Papers Committees.

International Electrotechnical Commission.—The U. S. National Committee of the International Electrotechnical Commission has held five meetings since December last. No convention or unofficial gathering of the Commission has been held during the year, but it is expected that an unofficial gathering will be held in Brussels in the week commencing August 7, 1910.

The following countries are now represented by national committees on the Commission: Argentina, Austria-Hungary, Belgium, Canada, Denmark, France, Germany, Great Britain, Italy, Japan, Mexico, Spain, Sweden, and the United States.

Informal communications have been exchanged with the General Secretary's office in London on the subject of a tentative plan for initiating international standardization in the direction of stationary direct-current generators and motors for continuous-service constant-potential operation.

Informal communications have also been exchanged with members of other national committees in regard to a proposed preliminary list of nine symbols for international adoption in electrical engineering, and the answers received have been very encouraging.

It is hoped that international progress may be made by the Commission in both of the above directions; namely, towards international standardization of machinery, and towards international standardization of symbols used in electrical engineering.

Library Committee.—We submit herewith our report giving the more important features of the growth and operation of the Library for the year ending April 30, 1910, together with a statement of the present condition of the several funds and expenditures for the year.

The gifts to the Library through its members and others have reached a total of 975 volumes and pamphlets. 287 volumes have been added through purchase and 54 volumes have been received through exchange for the PROCEEDINGS of the Institute. The total additions are therefore 1320 titles.

In the table of statistics given below a large number of pamphlets has been added which was received in the previous year but which had not been listed or accessioned at the time of the last report.

The total valuation is shown in the table below and a complete list of donors with the number of volumes or pamphlets presented by each is as follows:

Donors

ADAMS, S. C	3
AERONAUTIC SOCIETY OF NEW YORK	1
ALLEGEMEINE ELEKTRICITATS GESELLSCHRAFT	3
ALMANNA SVENSKA ELEKTRISKA AKTIEBOLAGET	1
ALUMINIUM COMPANY OF AMERICA	5
AMERICAN CIVIC ASSOCIATION	1
AMERICAN INSTITUTE OF ARCHITECTS	2
AMERICAN MINING CONGRESS	3
AMERICAN RAILWAY ASSOCIATION	7
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS	1
AMERICAN SOCIETY OF ENGINEERING CONTRACTORS	1
AMERICAN STREET AND INTERURBAN RAILWAY ASSOCIATION	6
ARMSTRONG CORK COMPANY	1
ARNOLD, B. J	1
ASSOCIATION OF LICENSED AUTOMOBILE ENGINEERS	1
ASSOCIATION OF VERMONT ENGINEERS	1
BAEYER, O. V	1
BAKER ELECTRIC COMPANY	2
BENTLEY, E. M	1
BOSTON SOCIETY FOR CIVIL ENGINEERS	1
BOSTON TRANSIT COMMISSION	1
BROOKLYN ENGINEERS CLUB	1
BURCH, E. P	1
BUREAU OF LONGITUDE, PARIS	1
CALDWELL, EDWARD	22
CAMBRIDGE (MASS.) BRIDGE COMMISSIONERS	1
CANADIAN ELECTRICAL ASSOCIATION	1
CANADIAN ENGINEER	1
CARNEGIE INSTITUTE OF WASHINGTON	4
CARNEGIE LIBRARY OF PITTSBURGH	1
CIVIC LEAGUE OF SAN FRANCISCO	3
CLARK, MYRON C. PUBLISHING COMPANY	1
CLAYTON, W. B. AND CRAIG, J. W	1
CLEVELAND ENGINEERING SOCIETY	1
COHRANE PUBLISHING COMPANY	1
COLUMBIA UNIVERSITY	9
COMISION 4 CONGRESO CIENTIFICO (CHILE)	3
CONNECTICUT BUREAU OF LABOR	1
CUSHING, H. C., JR	1
ELECTRIC TRADES ASSOCIATION OF THE PACIFIC COAST	1
ELECTROCHEMICAL & METALLURGICAL INDUSTRY	1
ENGINEERS CLUB OF CENTRAL PENNSYLVANIA	1
ENGINEERS CLUB OF PHILADELPHIA	1
ENGINEERS CLUB OF ST. LOUIS	1
ENGINEERS CLUB OF TORONTO	1
ENGINEERING STANDARDS COMMITTEE	1
FIDELITY & CASUALTY COMPANY OF NEW YORK	1
GENERAL ELECTRIC COMPANY (INCOMPLETE)	3

GESELLSCHAFT FUR DRAHTLOSE TELEGRAPHIE, BERLIN	1
GILBRETH, F.B	1
GUYE, P. A	1
HEDENBERG, MR	1
HOPELI, U	3
HUELS, F. W	1
HUNTINGTON, MR	1
L'INDUSTRIE DES TRAMWAYS ET CHEMINS DE FER	1
INSURANCE SOCIETY OF NEW YORK	2
INTERNATIONAL AMERICAN SCIENTIFIC CONGRESS	1
ISOLATED PLANT COMPANY	1
JENKS, W. J	4
KANSAS GAS, WATER, ELECTRIC LIGHT & STREET RAILWAY ASSOCIATION	1
KANSAS UNIVERSITY & ENGINEERING EXPERIMENT STATION	1
KENNELLY, A. E	5
KING, MOSES	1
LEWIS INSTITUTE	1
MCMILLAN COMPANY	3
MAILLOUX, C. O	1
MARTIN, JOHN	1
MARTIN, T. C	10
MASSACHUSETTS GAS & ELECTRIC LIGHT COMMISSIONERS	1
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	1
MCGRAW-HILL BOOK COMPANY	117
MICHIGAN ELECTRIC ASSOCIATION	1
MONTANA STATE COLLEGE OF AGRICULTURE & MECHANICS ARTS	1
MUNICIPAL SCHOOL OF TECHNOLOGY MANCHESTER	2
MUNICIPAL ENGINEERS IN THE CITY OF NEW YORK	2
NATIONAL ASSOCIATION OF CEMENT USERS	1
NAIONAL ASSOCIATION OF COTTON MANUFACTURERS	1
NATTIONAL FIRE PROTECTION ASSOCIATION, BOSTON	1
NATIONAL SOCIETY FOR THE PROMOTION OF INDUSTRIAL EDUCATION	2
NEW ORLEANS SEWERAGE & WATER BOARD	1
NEW YORK CITY BOARD OF MAGISTRATES	1
NEW YORK PUBLIC SERVICE COMMISSION, 2ND DISTRICT	22
NEW YORK PUBLIC SERVICE COMMISSION, 1ST DISTRICT	15
NEW YORK STATE EDUCATIONAL DEPARTMENT	2
NEW YORK STATE LABOR DEPARTMENT	1
NEW YORK STATE WATER SUPPLY COMMISSION	1
NEW YORK ELECTRICAL SOCIETY	1
NEW YORK UNIVERSITY	1
OHIO INDEPENDENT TELEPHONE ASSOCIATION	3
PFUND, RICHARD	3
PERU MINISTERO DE FOMENTO	1
PHYSIKALISCH TECHNISCHEN REISHSANSTALT	13
PITTSBURG CHAMBER OF COMMERCE	1
POTAMIAN BRO	1
ROBSON & ADEE	1
ROCHESTER ENGINEERING SOCIETY	1

SHELDON, SAMUEL	1	
SIEBEL, F. P	1	
SOCIETE INDUSTRIELLE DE L'EST NANCY	1	
SOCIETY OF NAVAL ARCHITECTS & MARINE ENGINEERS	11	
SPON & CHAMBERLAIN	4	
SPRINGER, J	1	
STONE & WEBSTER	1	
SUBMARINE SIGNAL COMPANY	9	
SYDNEY UNIVERSITY ENGINEERING SOCIETY	1	
TELEFUNKEN WIRELESS TELEGRAPH COMPANY	27	
TELEGRAPHIC HISTORIAL SOCIETY OF NORTH AMERICA	2	
THOMPSON, S	1	
TRAUTWINE J. C., JR. & J. C. 3RD	2	
U. S. CENSUS BUREAU	2	
U. S. COAST & GEODETIC SURVEY	8	
U. S. GEOLOGICAL SURVEY	8	
U. S. INTERSTATE COMMERCE COMMISSION	1	
U. S. LIBRARY OF CONGRESS	4	
U. S. NAVY DEPARTMENT	2	
U. S. STEAM ENGINEERING BUREAU	1	
U. S. WAR DEPARTMENT	1	
UNIVERSITY OF ILLINOIS—ENGINEERING EXPERIMENTAL STATION (12 NOS. 1 VOL.)	12	
UNIVERSITY OF OKLAHOMA	2	
UTAH UNIVERSITY OF ENGINEERS	1	
VAIL, T. N	1	
VAN NOSTRAND D. & COMPANY	8	
VILLARS, GAUTHIER	1	
WEAVER, W. D	2	
WENTWORTH, MR	1	
WESTERN ELECTRIC COMPANY	482	
WESTERN UNION TELEGRAPH COMPANY	1	
WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY	2	
WILEY, JOHN & SONS	1	
WIRELESS INSTITUTE OF NEW YORK	1	
WISCONSIN RAILROAD COMMISSION	1	
WORCESTER POLYTECHNIC INSTITUTE	1	
WYNKOOP, H. S	1	
DONORS UNKNOWN	30	
		979

Other Accessions:

Purchases	287	
Exchanges	54	341
Total Accessions		1320

In the report of one year ago there was outlined a new arrangement under which the library staff had been working. This same arrangement has continued this year with the same staff of employees.

The following tabulation gives the state of the five funds from, which the Library committee is entitled to draw.

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1909	$251.51		
Interest May 1, 1910	6.53	Unexpended	$258.04
	$258.04		$258.04

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications.

Balance May 1, 1910	$30.35		
Interest May 1, 1910	$30.00	Unexpended	$60.35
	$60.35		$60.35

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904 FUND

Invested in New York City 4½% Bonds	$2268
Additions to the fund	25
Total fund	$2293.80

Balance on hand May 1, 1909	$124.72	Expended	$85.60
Interest to May 1, 1910	90.00	Unexpended	129.12
	214.72		214.72

WEAVER FUND.

Balance on hand May 1, 1909	$65.44	Unexpended	$65.44
	$65.44		$65.44

INSTITUTE APPROPRIATION ACCOUNT.

Dr.		Cr.	
Appropriation for the year ending October 1, 1910	$3,500.00	Librarian and assistants	$1,569.69
		Cataloguing	255.02
		Desk attendant	138.67
		Insurance	80.33
		Binding	377.25
		Books	301.50
		Subscriptions	258.75
		Furniture and Fixtures	167.72
		Miscellaneous	116.80
			$3,265.73
		Unexpended	234.27
	$3,500.00		$3,500.00

The general statistics of the Library and its valuation are shown in the following tabulation:

STATISTICS OF LIBRARY, MAY 1, 1910

Source	Volumes	Pamphlets	Valuations
Report of May 1, 1909	13,515	565	$24,566.23
Purchases	287		522.94
Gifts and exchanges	1063		769.95
Old material accessioned		714	100.00
	14865	1279	$25,959.12

In the following table are given the figures for the total valuation of the library property:

Books	$25,959.12
Stacks	1,761.05
Furniture, Catalogues, cases, etc	376.00
	$28,096.17

LIBRARY ATTENDANCE

	Day	Night	Total
May 1909	462	221	683
June "	484	198	682
July "	472	Closed	472
August "	472	Closed	472
September "	434	220	654
October "	471	238	709
November "	479	223	702
December "	545	301	846
January 1910	460	286	746
February "	416	232	648
March "	439	256	695
April "	488	272	760
Total May 1909–April 1910	5622	2447	8069

NEW INDEXING

The very valuable set of telephone litigation records presented to the library a few years ago, comprising about 100 volumes have been thoroughly catalogued during the year. The total number of card entries required for this set was about 1300 and these are now incorporated in the general card catalogue of the library.

The general catalogue has also been increased by the addition of cards bearing all of the entries in the two-volume bibliography of the Wheeler collection published last year.

The splendid gift of the Western Electric Company deserves special mention. This consists of 482 volumes of United States Patent Office Certified Specifications, including a copy of every specification from May 30, 1871 to March 1896 and of every electrical specification from July 1887 to December 1907. The set makes a splendid foundation for a patent library. During the year the volumes of certified specifications from April 1896 to December 1906 were purchased, making the set now in the library complete from the beginning of the certified series to the end of 1906, and it is expected this will soon be brought up to date.

Another gift worthy of special mention is the Diary of Samuel F. B. Morse presented by Mr. Thomas A. Edison. This diary is 13 inches in length by 8 inches in width, a formal book of white ruled paper bound in stiff boards. The book contains some 45 pages of copies of official correspondence with the United States Treasury by Morse as Superintendent of Electromagnetic Telegraphs, followed by about 8 pages of personal notes. The dates range through 1843 and 1844 while some of the later entries are made in 1848. A full and sympathetic description by Mr. T. C. Martin of this interesting book with fac similes of some of its entries is printed in the Metropolitan Magazine for April 1910, under the appropriate title " From One Genius to Another: a forgotten diary of S. B. Morse and how it was found by Thomas A. Edison."

Mr. Edward D. Adams has continued his contributions to the library as in previous years by the donation of the PROCEEDINGS and TRANSACTIONS of the Royal Society of London, and new volumes of the International Catalogue of Scientific Literature. He has also as heretofore had these volumes bound at his expense.

The " C. O. Mailloux Fund " of $1000 has again been used to maintain the four important periodical sets which were originally presented to the library by Mr. Mailloux.

Law Committee.—Various questions have been submitted to this committee for consideration and report within the last year. The most important work of the committee, however, has been in connection with its report on the proposed formation of technical sections of the Institute, and its work in respect to the proposed amendments to the Constitution.

Conservation of Natural Resources Committee.—Owing to the series of investigations which have been in progress in Washington during the greater part of the year, into affairs connected with the conservation of natural resources, the committee deemed it inadvisable to take any active part in connection with conservation until the above mentioned investigations have been completed.

Edison Medal Committee.—On May 18, 1909, the committee awarded to Trygve Jensen, a graduate student of the University of Illinois, the student Diploma of Merit and a cash sum of $150, for his record of research, entitled, " Operation of a 100,000-volt Transformer."

The revised by-laws of the committee, made necessary by the new trust deed, executed on March 26, 1908, were approved by the Board of Directors on May 18, 1909, and are now operative.

The work of the committee during the past year was particularly signalized by the award of the Edison Medal for the first time since the trust creating the medal was established in 1904. The award, for the year 1909, was made on December 16 last to Dr. Elihu Thomson, " For Meritorious Achievement in Electrical Engineering and Arts, as Exemplified in his Contributions Thereto During the Past Thirty Years." The parchment certificate constituting the official notice of the award was presented to Dr. Thomson at the annual dinner of the Institute on February 24, 1910, and the gold medal will be ready for presentation at the annual meeting on May 17.

It is believed that the administrative affairs of the Medal Committee have now been brought into such efficient and working order as to insure hereafter an annual award of the medal.

John Fritz Medal Board of Award.—The John Fritz Medal for 1910 is to be presented to Alfred Noble, for notable achievements as a civil engineer. A special committee has arranged for the presentation, which will be made in the fall of this year. This will be the sixth award of the Medal since its first presentation to Lord Kelvin in 1905.

Board of Examiners.—The Board has held 10 meetings during the year It has considered and reported to the Board of Directors a total of 1,397 applications for Associate election, Student enrolment, and transfer to the grade of Member. A summary of these applications is as follows:

Recommended for election as Associates	814
Recommended for enrolment as Students	507
Recommended for transfer to the grade of Member	47
Not recommended for election as Associates	3
Not recommended for transfer to the grade of Member	26
Total number of applications considered	1,397

The Board has received much assistance during the year from its Local Representatives, of which there are now seven, located in various cities in the United States, Canada, and Mexico.

Membership Committee.—During the year this committee has been active in bringing the advantages of Institute membership to the attention of desirable non-members.

In response to the Committee's general letter of November 8, 1909 requesting the membership to submit names of desirable candidates for admission as Associates, over 1500 names were suggested. All of these were communicated with by letter, accompanied by printed matter regarding the work of the Institute.

The number of applications received from November 1, 1909, at which time the present committee became active to April 30, 1910, is 558 and the total number received during the entire year is 848.

The present total membership and the increase during the past year are indicated below:

	Hon. Mem.	Mem.	Assoc.	Total
Membership, April 30, 1909	1	607	5,792	6,400
Additions:				
New Associates			910	
Transferred		48		
Deductions:				
Died		6	25	
Resigned		2	108	
Dropped		6	482	
Transferred			48	
Membership April 30, 1910	1	641	6,039	6,681

Net increase during the year in membership..........281

The net increase in membership was affected by the recent change in the by-laws. Formerly, a member could be in arrears for three years' dues before being dropped from membership, but under the present by-laws any member who on May 1 is in arrears for one year's dues is dropped as delinquent. This resulted in an unusually large number being dropped on May 1, 1909.

Resignations.—The following Members and Associates have resigned during the year in good standing.

Members.—Robert Hammond, F. M. Pedersen.

Associates.—G. A. Archer, L. T. Arnold, E. R. Avery, J. W. Aylsworth, L. Beauchamp, A. C. Babson, W. A. Baehr, R. Balfour, A. Balsley, W. C.

Barnes, M. H. Bentley, H. Binney, C. O. Bourne, J. Broich, C. C. Brown, M. C. Canfield, Eugene Carpenter, S. D. Coffin, F. W. Conn, A. S. Cross, E. H. Cutler, E. W. Cutler, W. B. Dodds, W. A. Drysdale, H. S. Elliott, W. C. Farnell, C. H. Felker, W. S. Finlay, F. H. Foster, Thomas French, Jr., W. H. Glenn, E. W. Goffin, H. de C. Hamilton, W. L. Harraden, W. W. Harris, A. S. Hart, R. Hawxhurst, F. J. Heavens, G. Hellebuck, S. M. Henry, C. W. Hogan, M. B. Holt, E. H. Hoppenstadt, J. H. Hubbs, C. Huper, C. S. Jameson, A. S. Kellogg, A. D. Kenyon, W. A. Kohn, E. Landon, E. C. Laudenberger, M. LeBlanc, A. J. Lowndes, D. Lowson, G. W. MacDonald, H. R. Markel, H. B. Marsh, Hobart Mason, E. M. McCleary, J. H. McConnell, J. L. McKay, W. A. McTaggart, H. S. Meyer, H. M. Migenault, W. H. Miller, N. N. Moneypenny, H. B. Morrell, L. H. Mueller, J. E. Murphy, G. B. Nichols, J. P. O'Donohue, W. N. Parsons, W. W. Patrick, W. J. Peaker, J. Peterson, F. L. Pircher, C. H. Porter, R. H. Read, I. W. Reynolds, C. L. Riley, C. E. Robertson, E. E. Rojahn, C. R. Scott, L. M. Schmidt, H. H. Seaman, C. E. Sedgwick, Sebastian Senstius, G. A. Sherman, S. Aylmer-Small, O. C. Snider, W. M. Stine, H. F. Strickland, A. E. Swan, A. S. Terry, G. C. Thomas, W. H. Tolman, G. A. Tower, L. Van Cott, J. Vandergande, J. H. Warder, F. Wenner, Jefferson Wetzler, R. Wilkander, S. E. Woodbury, L. M. Wright, A Wunderlich, R. E. Wyllie, L. G. Yochum.

Total resignations, 110.

Deaths.—The following deaths have occurred during the year:

Members.—C. B. Dudley, A. A. Knudson, J. J. Mahoney, J. T. Marshall, Townsend Wolcott.

Associates.—E. T. Alburger, Jr., F. C. Almond, J. W. Bridge, E. A. Briscoe, C. L. Buckingham, W. D. Buckman, H. J. Buddy, A. H. Demrich, T. Hirokawa, S. J. Houston, J. R. Jacobson, G. A. Joffe, A. P. Kennedy, D. Kos, I. Loveridge, W. W. Lyon, Jr., Robert Mitchell, A. W. K. Pierce, C. J. Toerring, J. C. Reilly, Ralph Scott, F. N. Simpson, G. W. Thompson, F. G. Tracy, H. E. Wagganan, C. I. Zimmerman.

Total deaths, 31.

Delinquent.—Dropped as delinquent during the year, 482.

Building Fund.—The amount collected from subscribers during the year was $2,552.15. The interest on the bank balances amounted to $585.25. These items make a total to the credit of the Building Fund during the year, of $3,137.40. A payment of $27,000. on account of the principal of the mortgage, was made during the year.

LAND, BUILDING AND ENDOWMENT FUND.

RECEIPTS.		DISBURSEMENTS.	
Before appointment of Committee	$ 6,100.00	Paid United Engineering Society, acct. of contract	$ 8,000.00
Collected by Committee	145,881.05	Paid United Engineering Society, acct. of mortgage	126,000.00
Interest on balances	5,967.01	Paid United Engineering Society, acct. of interest	19,529.45
Reimbursement by Institute	9,221.95	Expenses of Committee	10,440.73
		Balance in bank, May 1, 1910	3,199.83
Total	$167,170.01	Total	$167,170.01

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1904	1905	1906	1907	1908	1909	1910
Membership, April 30th, each year.	3027	3460	3870	4521	5674	6400	6681
Receipts per Member.	$13.66	$12.32	$12.77	$12.21	$13.01	$13.21	$13.35
Disbursements per Member:	$12.02	$10.72	$10.48	$11.62	$11.73	$10.49	$12.03
Credit Balance per Member	$0.64	$1.60	$2.29	.59	$1.28	2.72	1.32

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of this Committee.

May 17, 1910.

Mr. Lewis B. Stillwell,
President American Institute of Electrical Engineers,
No. 33 West 39th Street, New York City, N. Y.

Dear Sir: In accordance with past practice, your Finance Committee respectfully submits the following annual report:

During the past year the Committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise has performed the duties prescribed for it in the Constitution and By-Laws. Messrs. Peirce, Struss & Company, the chartered accountants, have audited the Institute books, and attached hereto is their certificate of the Institute's finances.

In company with your Treasurer and a member of the firm of chartered accountants, the Committee has examined the securities held by the Institute, and find them to be as stated in the accountants' report.

It is of interest to call attention to an additional payment of $27,000 towards the liquidation of the Institute indebtedness on the land on which the United Engineering Society's Building stands. By the payment of this sum, we have anticipated our obligations up to 1919, thereby proportionately reducing the annual interest payment.

In closing this report it seems proper to call attention to the fact, that the income for the Institute, estimated for the year in advance, has been exceeded by the actual income, so that even with an increased budget of expenditures by reason of the Institute's extended activities, it has been possible to close the fiscal year with a comfortable surplus.

Respectfully submitted,
Calvert Townley,
Chairman Finance Committee.

New York, May 10, 1910.

Mr. Calvert Townley,
Chairman Committee on Finance.

Dear Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1910.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit A. Balance Sheet, April 30, 1910.

Exhibit B. Receipts and Disbursements for general purposes for year ended April 30, 1910.

Exhibit C. Receipts and Donations for designated purposes also expenditures for year ended April 30, 1910.

Exhibit D. Condensed Cash Statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
(Signed) Peirce, Struss & Co.
Certified Public Accountants.

New York, May 10, 1910.

Mr. Calvert Townley,
Chairman, Committee on Finance.

Dear Sir: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1910, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1910, and that the accompanying statements of Cash Receipts and Disbursements are correct.

(Signed) Peirce, Struss & Co.
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

BALANCE SHEET, APRIL 30, 1910.

EXHIBIT A.

ASSETS.		
CASH:		
Land, Building and Endowment Fund	$3,199.83	
General Library fund	258.04	
Compounded Membership fund	5,018.24	
Mailloux fund, principal	1,000.00	
		$9,476.11
General Cash in bank	17,802.98	
Mailloux fund, interest	60.35	
Weaver donation	65.44	
International Elec. Congress of St. Louis Library fund, interest	154.92	
Total cash deposit	18,083.69	
Secretary's petty cash on hand	750.00	
		18,833.69
Land, Building and Endowment fund, accrued interest	70.37	
General Library fund accrued interest	2.69	
Compounded Membership fund accrued interest	58.31	
International Electrical Congress of St. Louis, 1904, Library Fund accrued interest	45.00	
		176.37
International Electrical Congress of St. Louis 1904, Library Fund, Bonds	2,268.00	
		2,268.00
New York City 4½% Gold Bonds	30,000.00	
Premium on bonds	1,952.50	
		31,952.50
Westinghouse Electric & Mfg. Co's. stock		50.00
Equity in Engineering Societies Building (25 to 33 West 39th St.)	353,346.61	
One-third cost of land (25 to 33 West 39th St.)	180,000.00	
		533,346.61
Library Volumes and Fixtures	27,309.14	
Transactions	7,446.25	
Office Furniture and Fixtures	6,692.20	
Works of Art, Paintings, etc	2,543.60	
Badges	517.05	
		44,508.24
ACCOUNTS RECEIVABLE:		
Members for current dues	660.00	
Members for past dues, suspense account	7,794.00	
Members for entrance fees	325.00	
Miscellaneous	494.18	
For Advertising	2,356.25	
Accrued interest on Bonds	675.00	
Accrued interest on bank balance	219.25	
		12,523.68
Total Assets		$653,135.20

LIABILITIES AND SURPLUS.		
FUNDS:		
Land, Building and Endowment Fund	$3,270.20	
General Library Fund	260.73	
Compounded Membership Fund	5,076.55	
Mailloux Fund	1,060.35	
International Electrical Congress of St. Louis 1904, Library Fund:		
Bonds	2,268.00	
Cash, on deposit.	154.92	
Accrued Interest.	45.00	
		$12,135.75
Reserve, for Furniture and Fixtures.		1,568.78
Accounts payable, subject to approval by the Finance Committee		4,558.34
United Engineering Society (for cost of land)		54,000.00
Total Liabilities		72,262.87
SURPLUS:		
In Cash	17,802.98	
NewYorkCity bonds	31,952.50	
In property and accounts receivable.	531,116.85	
		580,872.33
Total Liabilities and surplus.		$653,135.20

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1910.

EXHIBIT B.

RECEIPTS.		
Entrance Fees	$4,265.00	
Current Dues	59,943.37	
Past Dues	5,541.75	
Advance Dues	112.50	
Students Dues	3,984.00	
Transfer Fees	500.00	
Badges	1,875.00	
		76,221.62
Sales, Transactions, etc.	1,477.43	
Subscriptions, Proceedings	1,669.57	
Advertising	7,727.00	
Binding	136.10	
Exchange	26.74	
INTEREST:		
Bonds	1,350.00	
Bank Balance	591.42	
		12,978.26
		$89,199.88

DISBURSEMENTS.		
Stationery and Printing	$2,924.98	
Postage	2,466.81	
General Expenses	2,350.67	
Meeting Expenses	3,318.54	
Section Meetings	7,257.99	
Badges purchased	1,694.74	
Salaries	9,915.50	
Interest on Mtge	3,240.00	
Bibliography	741.18	
Office Furniture	497.65	
Advertising Expense	3,267.38	
Year Book and Catalogue	2,616.16	
Express	466.47	
Miscellaneous	20.70	
		$40,778.77
PROCEEDINGS:		
Printing, paper, binding, engraving	16,096.86	
Salaries	3,400.00	
		19,496.86
TRANSACTIONS:		
Vol. 27		8,623.46
Vol. 28		2,595.87
LIBRARY (including salaries)		3,265 73
UNITED ENGINEERING SOCIETY.. Assessments for office space		5,333.35
Total		80,094.04
Excess Receipts over Disbursements		9,105.84
		$89,199.88

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1910.

EXHIBIT C.

RECEIPTS.	
Land, Building and Endowment Fund, Donations, Interest, etc.	$3,137.40
General Library Fund, Interest	6.53
Compounded Membership Fund, Interest	189.54
International Electrical Congress of St. Louis 1904, Library Fund, Donations and interest	115.80
Mailloux Fund, Interest	60.00
Total	$3,509.27

EXPENDITURES.	
Land Building, and Endowment Fund, on account of mortgage	27,000.00
Compounded Membership Fund	526.87
International Electrical Congress of St. Louis 1904 Library Fund	85.60
Special Library account (to be reimbursed)	61.00
Total	$27,673.47

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONDENSED CASH STATEMENT.

EXHIBIT D.

Cash on deposit April 30, 1909	$42,868.16	
Secretary's Petty Cash, April 30, 1909	500.00	
		$43,368.16
Receipts for general purposes, Exhibit " B "	89,199.88	
Receipts for designated purposes, Exhibit " C "	3,509.27	
		92,709.15
		$136,077.31
Disbursements for general purposes Exhibit " B "	80,094.04	
Expenditures for designated purposes, Exhibit " C "	27,673.47	
		107,767.51
Balance on hand April 30, 1910		28,309.80
On deposit for designated purposes, Exhibit " A "	9,476.11	
*On deposit in General cash, Exhibit " A "	18,083.69	
Secretary's Petty Cash, Exhibit " A "	750.00	
		28,309.80
Property acquired during the year, Office Furniture and Fixtures		497.65

*This includes the following unexpended balances:

Mailloux Fund	$60.35
Weaver Donation	65.44
Int. Elec. Congress of St. Louis Library Fund	154.92
	$280.71

Respectfully submitted for the Board of Directors

RALPH W. POPE, Secretary.

New York, May 17, 1910.